ERDC/CRREL TR-13-8

Cold Regions Research
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Thule Air Base Airfield White Painting and Permafrost Investigation

Phases I–IV

Kevin Bjella

June 2013

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Cold Regions Research and Engineering Laboratory
U.S. Army Engineer Research and Development Center
72 Lyme Road
Hanover, NH 03755

Final report

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Prepared for U.S. Air Force, 21st Civil Engineering Squadron, 821st Air Base Group
Peterson Air Force Base, Colorado

Abstract

In the late 1950s, white painting of the airfield at Thule Air Base, Greenland, was started to prevent thawing of ice-rich native permafrost soils that had caused localized depressions in the runway and taxiways. Unfortunately, the painting reduces the braking ability of the aircraft, and increases the costs of operation. Cost-effective alternatives to white painting do exist, such as insulating the subgrade, which was tested at Thule in this study, or over-excavating the ice-rich soils. These solutions can be implemented during the next repaving cycle, eliminating the white painting entirely, and saving future costs. Additionally, the white painting over the entire airfield should be halted. This will allow monitoring of thaw stability, better determining the ultimate extent of the few critical locations requiring thaw mitigation, and providing valuable information to efficiently design the thaw prevention techniques in the upcoming repaving. There will be some minor thaw settlement at a few areas during the time between halting painting and repaving. However, the settlement will not be catastrophic and will not decrease the reliability and operation of the airfield, and can be repaired with knowledge and equipment currently available. Diligent monitoring for any settlement will ensure that this procedure creates no adverse impact.

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Preface

The work was performed by Kevin Bjella (Force Projection and Sustainment Branch, Dr. Edel Cortez, Chief), U.S. Army Engineer Research and Development Center–Cold Regions Research and Engineering Laboratory (ERDC-CRREL). At the time of publication, Dr. Justin Berman was Chief of the Research and Engineering Division. The Deputy Director of ERDC-CRREL was Dr. Lance Hansen and the Director was Dr. Robert Davis.

The author thanks Stephanie Saari, Art Gelvin, Marc Beede ,and Seth Campbell for their invaluable assistance with the field work. The author also thanks Greenland Contractors personnel for their support during the field work of this project.

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COL Kevin J. Wilson was the Commander and Executive Director of ERDC, and Dr. Jeffery P. Holland was the Director.

Unit Conversion Factors

Multiply	By	To Obtain
degrees Fahrenheit	(F-32)/1.8	degrees Celsius
feet	0.3048	meters
gallons (U.S. liquid)	3.785412×10^{-3}	cubic meters
inches	0.0254	meters
miles (U.S. statute)	1,609.347	meters
pounds (force) per square inch	6.894757	kilopascals
pounds (mass)	0.45359237	kilograms

Executive Summary

In the late 1950s, the U.S. Air Force began white painting the airfield at Thule Air Base, Greenland, to prevent thawing of ice-rich native permafrost soils that caused localized depressions in the runway and taxiways. Unfortunately, painting reduces the braking ability of the aircraft, and increases the costs for operation of the facility. In 2008, a multi-phase study was started to understand the reasoning and efficacy of the painting, and to suggest alternatives that could be applied during the next repaving cycle scheduled to start FY13 or later.

The results of the study show that ice-rich permafrost does not exist at shallow depths under the entire airfield. It exists only at localized areas, despite what might be suggested by painting the entire airfield. White painting effectively raises the albedo, preventing summer heat energy from thawing the full depth of approximately 6 ft to the ice-rich soils. This prevents thaw settlement and shallow depressions at the surface. However, the paint must be maintained in pristine, white condition throughout every summer to be effective. Through a half century of painting, a moderately white condition has been maintained at best. During the last three summer seasons, from 2009 to the present, the paint cover has been least effective along the keel (centerline) of the runway. From runway station* 61+00 to 75+00, a change in runway slope design in 1952 caused fill thickness to be less than the 6.0 ft† as prescribed, and this coincides with the current location of thaw depressions from approximately stations 60+00 to 70+00.

Cost effective alternatives to extensive white painting do exist. The subgrade can be insulated, which was tested at Thule in this study, or ice-rich soils can be “over-excavated.” These are common permafrost engineering methods practiced in Alaska, Canada, and Russia today. These localized solutions can be used during the next repaving cycle, eliminating the white painting over the airfield entirely, and saving future costs for materials and manpower.

* This report follows previous Thule AB report convention where stationing begins at 00+00 at the threshold of the 08 end (west) and ends at 99 +97 at the threshold of the 26 end (east). The stationing is referenced at the centerline of the runway unless otherwise specified. Also the term *airfield* is meant to describe all paved surfaces, including the runway, taxiways, and ramps.

† Customary units are used for ease in translation from the various literature sources.

In the meantime, the white painting over the entire airfield should be halted. This will provide an opportunity to monitor thaw stability, to better determine the ultimate extent of the few critical locations requiring thaw mitigation, and to provide valuable information to efficiently design thaw prevention techniques in the upcoming repaving. Some minor thaw settlement may be expected at a few localized areas after paint maintenance ends and before the scheduled repaving. However, settlement will not be catastrophic and will not affect the reliability and operation of the airfield. It can be repaired with knowledge and equipment currently available at the Air Base. Diligent monitoring of the airfield for any settlement will ensure that this procedure has no adverse effects.

1 Background and Introduction

Thule Air Base (Thule) is located on a soil and vegetated margin situated between the Greenland Ice Sheet to the east and the coastline of North Star Bay to the west (Fig. 1). The Air Base sits in a valley (Pituffik) with bedrock ridges to the north and south known as North Mountain and South Mountain, respectively. The valley is drained east to west by the North River located immediately north of the base.

Figure 1. Regional location of Thule Air Base in northwest Greenland (1 in. = 5.0 mi).

1.1 Current issues

After construction was completed in 1951 (Fig. 2), areas of settlement were observed in the runway and located around the 60+00 and 70+00 areas. This settlement was surmised to be the thawing of native permafrost soils below the runway embankment. A study was conducted in 1953 and 1954, where the naturally black asphalt pavement was painted white to increase albedo (ratio of reflected vs. incoming solar radiation) and reduce summer thaw depth (ACFEL 1955). This demonstrated that the thaw depth could be reduced by nearly 2 ft, and, subsequently, white painting was initiated.

Currently, white painting is done over the entire active surface of the airfield (more than 4,000,000 ft^2).

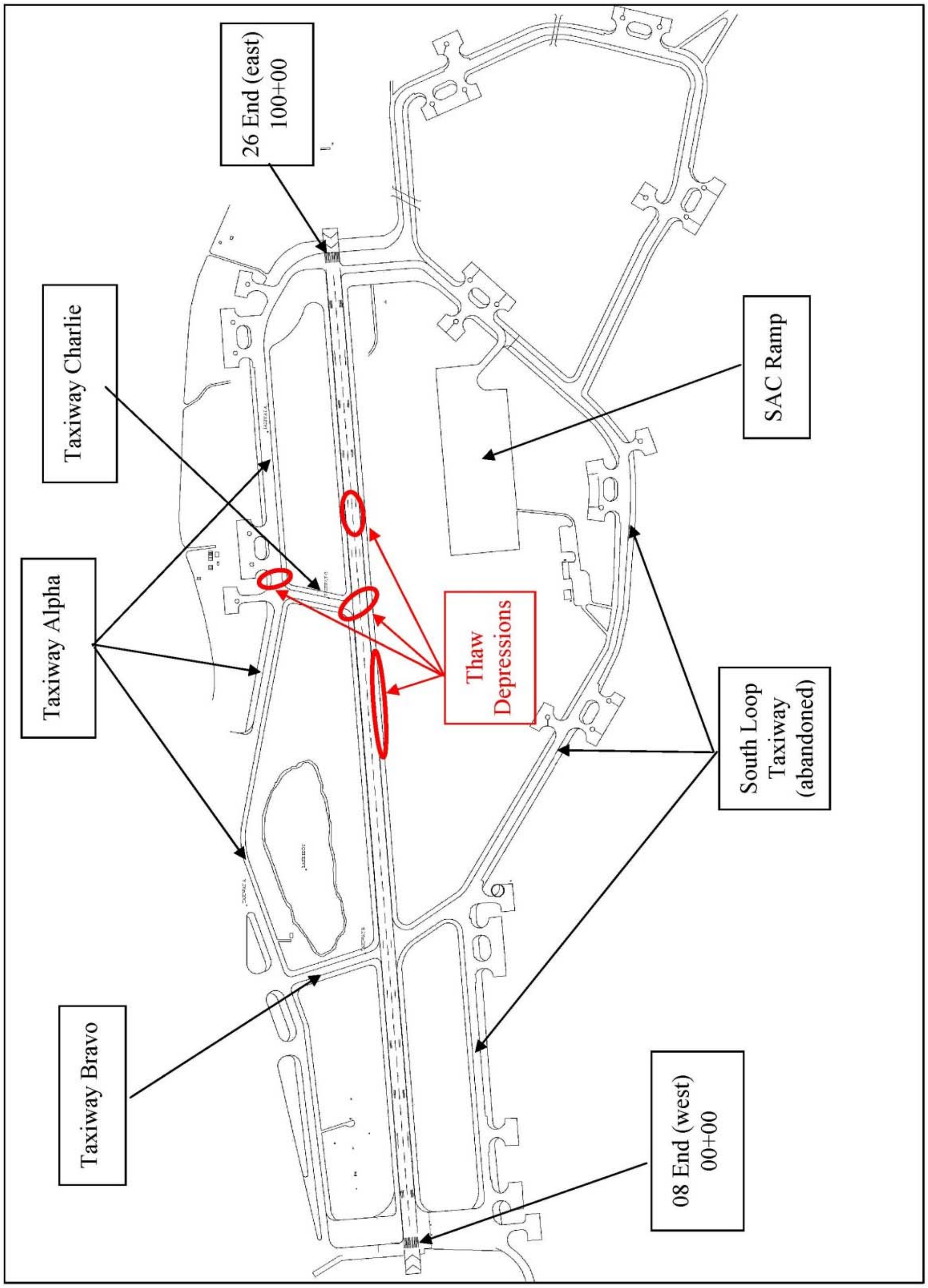

Figure 2. Airfield layout at Thule Air Base (1 in. = 1700 ft).

Unfortunately, the white painting reduces the braking ability of the aircraft and reduces visibility of the airfield in the winter, causing safety concerns.

Also, the cost is very high, both in manpower and materials. The runway was last repaved in 1992, and is scheduled to be repaved again in FY13. Depressions have appeared since the last repaving, most notably across the runway at the intersection with Taxiway Charlie, and across Taxiway Alpha near the intersection with Cluster Pit 2 and 3. These depressions measure 2 to 3 ft in width, 3 to 5 ft in length, and 1.0 to 2 in. deep. Severe depressions (up to 6 in. deep) are found in the paved area outside of the runway edge lighting, from 43+00 to 50+00, on the south side of the runway. However, this area was not repaved in 1992.

Additionally, groundwater seeps from a few runway, shoulder, and taxiway locations. Seepage is greatest and most notable during the spring. A few locations have flow coming from cracks in the asphalt in the runway shoulders and taxiway shoulders, water filling and flowing from lighting fixtures in shoulder areas, and continual flow from locations on embankment shoulders. Also, during spring runoff, surface water inundates the abandoned south loop taxiway at two locations. In locations of seepage, deterioration of the asphalt is notable with substantial cracking, undulations, and small potholes. The flow gradually subsides through the summer months. To date groundwater has not seeped onto the asphalt during winter.

This study was commissioned to investigate alternatives to the white painting that can be implemented during the next repaving. Phase I of the study began in 2008, and Phase IV was completed during the 2011 field season. This report is designed to be compilation of results (Bjella 2008, 2010). The reader should consult the previous reports for details of all the investigations to date. Of special interest, Bjella (2008) describes the basic aspects of permafrost and permafrost engineering, and Bjella (2010) describes the field work to that date.

1.2 Investigation methodology

To ensure a thorough investigation, all the issues affecting the current state of the airfield needed to be understood. This includes the natural environment before and after construction, the history and reasoning for the engineering decisions made, and the consequences resulting from those decisions. The study was composed of three components: literature search, field investigation, and investigation of alternatives. This information is compiled into a summary with recommendations.

1.3 Existing information

This study began with a literature search of engineering reports, research reports, airfield condition reports, existing photography, and discussions with personnel familiar with the airfield history and operation. Nearly all information in print was reviewed, with the exception of some early photography. This information provided a background to work with for the field investigation.

1.4 Field investigation

Field investigations were required to corroborate the literature information, to help understand how the natural environment existed prior to construction, how it exists now since the construction, and the effectiveness of the white painting. The field study included test pits, subsurface borings, surface-based geophysical techniques, and solar radiation measurements.

1.5 Alternatives

White painting is one method of reducing thaw depth under a paved structure. Other alternatives exist and were investigated for effectiveness.

2 Site Conditions

2.1 Current climate

Thule AB has arctic marine weather, modified by the proximity to the inland ice cap. The mean annual air temperature (MAAT) is −11.0°C with occasional hurricane force winds. The average air thawing degree-days (ATDD) for 1953 to 2011 is 428°C, and the average air-freezing degree-days (AFDD) for the same period is 4414°C. The approximate length of the thawing season is 125 days from mid-May to mid-September. Air thawing and freezing indexes are a seasonal summation of the average number of degrees above freezing (thaw index) or below freezing (freeze index) for each day of the season. These indices are a convenient method to compare variation in climate from year to year, and for input into models for the prediction of thaw and freeze depth.

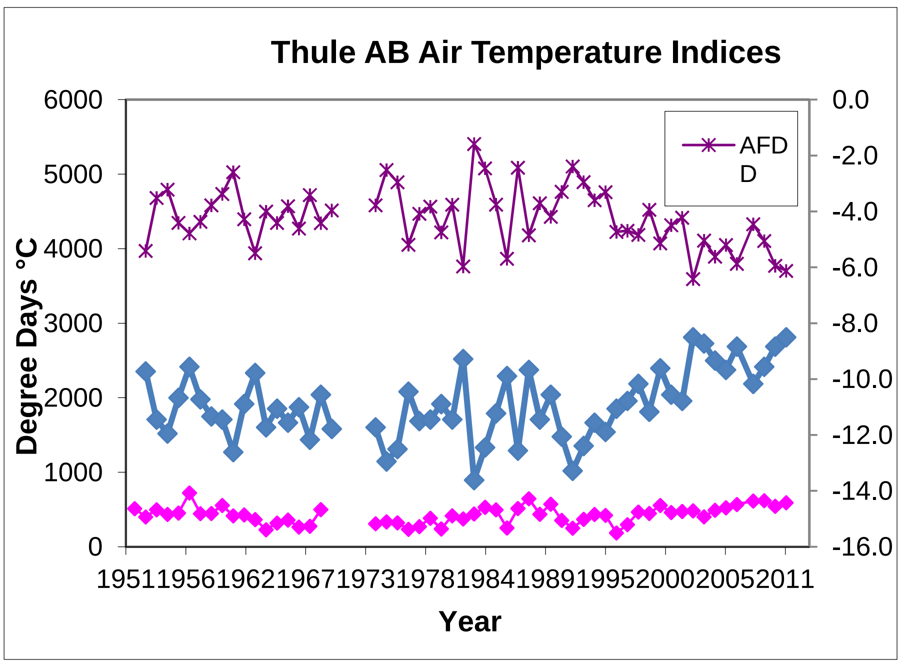

Figure 3. Plot of air freezing and thawing indices for 1952 to 2011, Thule AB. A slight trend to warmer winters is noticeable.

The indices are given in Table 1. Plotted in Figure 3 are daily surface data from Station #042020 Pituffik (Thule AB, Greenland), obtained through the U.S. National Climatic Data Center, for 1952 to 2011. Based on these indices, the thaw index has exceeded the average of 428°C degree-days for the last 7 years, and the summer of 2009 was the third warmest since

1952. The average freeze index of 4414°C degree-days has not been attained for the last 9 years; this is a possible trend towards warmer winters. A statistical analysis was not done; however, if this trend is confirmed, it would coincide with other Arctic observations that point towards warming winters with approximately stable summers (IPCC 2007).

Table 1. Air freeze and thaw indexes, Thule AB. Values in red are the five warmest seasons.

Year	ATDD max °C Days	AFDD max °C Days		Year	ATDD max °C Days	AFDD max °C Days
1952	513	NR		1983	441	5406
1953	401	3971		1984	531	5080
1954	498	4682		1985	496	4593
1955	435	4794		1986	254	3866
1956	453	4348		1987	515	5088
1957	723	4207		1988	646	4181
1958	445	4362		1989	437	4611
1959	448	4583		1990	572	4428
1960	556	4735		1991	355	4764
1961	416	5027		1992	250	5104
1962	428	4396		1993	369	4895
1963	366	3940		1994	435	4652
1964	229	4499		1995	423	4760
1965	319	4347		1996	186	4226
1966	360	4571		1997	298	4242
1967	266	4271		1998	466	4186
1968	276	4721		1999	448	4523
1969	500	4344		2000	556	4072
1970	NR	4515		2001	461	4316
1971	NR	NR		2002	475	4417
1972	NR	NR		2003	483	3594
1973	NR	NR		2004	402	4110
1974	310	4583		2005	491	3894
1975	335	5057		2006	524	4050
1976	322	4893		2007	568	3798
1977	235	4053		2008	615	4329
1978	271	4470		2009	619	4104
1979	384	4566		2010	544	3771
1980	241	4220		2011	592	3703
1981	417	4592		Min	186	3594
1982	375	3763		Max	723	5406
				Mean	428	4414

2.2 Geology

The glacially sculpted geology of the region is dominated by an alternating sequence of sedimentary rocks, termed the Thule Supergroup. More specifically, the Upper Thule Supergroup is sediments composed of the Narssarssuk Group and the Dundas group (Dawes 2006). These siliciclastic redbeds and pale carbonaceous sediments are visible in the glacially eroded slopes of North and South Mountain, Dundas Fjeld, and Saunders Ø. These lithified sediments are essentially undeformed; however, half-grabben structures are numerous, displaying vertical displacements of hundreds to thousands of feet (Davies et al. 1963). A regional swarm of basic dikes and sills are noted in this group, with a prominent exposure of Diorite having been cut for the runway at approximately 70+00. These strata generally dip to the south-southwest at shallow angles, with the strike trending west-northwest, consistent with the trend of the North River Valley. Prominent exposures of the mudstone (slate) sequences can be found in the valley and leading up to, and at, the Ballistic Missile Early Warning Site (BMEWS) site. The layers are hundredths of an inch in thickness, dark colored, and smooth. Weathering creates ready detachment at the bedding boundary, and exposures are easily disturbed by hand and foot traffic. Bedrock is relatively shallow at the project site.

2.3 Glaciology

The glacial history of the region described by Funder (1990) suggests that during the late Pleistocene, multiple glacial advances covered the Pituffik Valley. The greatest extent of glaciation and the earliest recorded in the existing sediments, the Agpat Glaciation, extended westward beyond Saunders Ø. The extent of the following inter-glacial period is undetermined, but the ice is thought to have retreated to Wolstenholm Fjord. The following glacial advance, the Narssarssuk Glaciation, filled Pituffik Valley and extended southwestward, terminating on the plateau to the south of the valley. The following inter-glacial period is thought to have caused retreat to Wolstenholm Fjord. The next and last glacial advance, in the early Holocene, failed to progress from Wolstenholm Fjord, and no further advances in the valley are noted. Owing to the multiple glacial events, a large amount of outwash and glacial till sediment overlies the sedimentary bedrock within Pituffik Valley. The glacial sediment thickness varies from 15 to 60 ft at the location of the Air Base, progressively deepening towards the existing ice cap margin, and thinning to beds of sand when approaching the beaches of North Star Bugt. Glacial tills of larger cobble and errat-

ics are evident in the valley. The Air Base is situated on glacial sediments of varying thickness, with an average of 10 to 30 ft at the airfield. During the glaciations, alluvial sediments have been deposited along the channel of the North River. These deposits have reworked the outwash and till into more stratified layers of silts, sands, and gravels.

2.4 Permafrost and ground ice

A periglacial environment has existed in the High Arctic through the Pleistocene and Holocene, and continues today, including the Pituffik Valley. During glacial retreat, the terrestrial sediments and bedrock are exposed to the low temperatures of the period, allowing permanently frozen ground (permafrost) and associated ground ice features to establish. In High Arctic areas, such as Pituffik, the permafrost is continuous in lateral extent, and is estimated to be more than 1000 ft deep. This permafrost was created epigenetically, meaning the sediments and rock were placed then subsequently permanently frozen. The current permafrost temperature at the depth of zero annual amplitude is approximately −10°C, measured with a 40-ft-long thermistor string installed in an undisturbed location near the airfield (Fig. 4). The permafrost will be thawed to some depth under large and continually existent water bodies, such as Lake Eddy and the North River.

Ice exists in permafrost and is the primary concern for engineering foundations for structures. If the ice is allowed to thaw, the greater the amount of ice present, the lower the shear strength of the soil will be upon thawing. This lower shear strength results in differential thaw settlement and must be accounted for in design. Within the Pituffik Valley, the topography provides for higher ground that is better drained and, therefore, contains less ice by volume. The adjacent lower ground serves as surface water pathways and also for water storage in small lakes. This lower ground is poorly drained and is subsequently more ice rich.

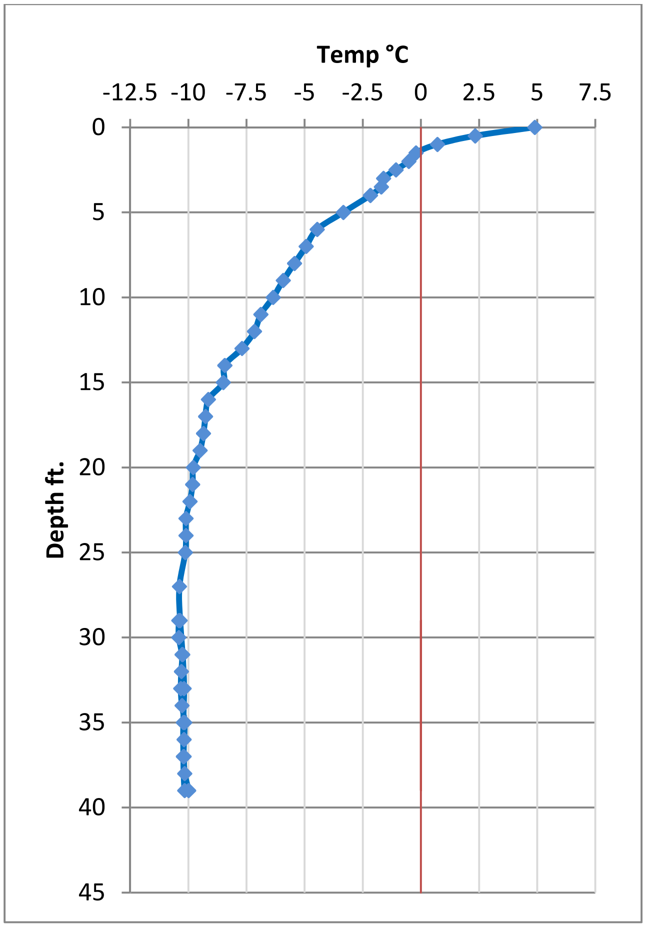

Figure 4. Plot of undisturbed permafrost temperature down to 40 ft below the surface. The depth of zero annual amplitude is approximately at 25 ft where the permafrost is approximately −10.0°C.

2.4.1 Matrix ice

It is generally assumed that soils are saturated when they become permanently frozen. The 10% volume expansion that fresh water experiences upon freezing will cause individual soil particles to move apart during creation of the matrix ice. Fine grain soils contain more water (ice) at saturation than do coarser grain soils (Williams and Smith 1989). Because of this, fine grained soils are generally considered thaw-unstable, while coarse grained soils are generally considered thaw-stable. The glacial sediments in the Pituffik Valley are composed of both fine and coarse grained soils, in addition to other forms of excess ice.

2.4.2 Wedge ice

Low winter temperatures contract surface soils and allow cracks to develop that are tens of feet deep, many tens of feet in length, and up to 0.5 in. wide. During spring and summer, surface water migrates into the cracks and freezes, creating a thin vein of ice. This location of ice intrusion is a zone of weakness. The process will repeat at the same location for hundreds and thousands of years, with the resultant ice vein becoming an ice wedge. These wedges can be tens of feet in depth, 3 to 5 ft wide, and many tens of feet in length (Fig. 5). Most often, the wedges will interconnect into polygon shapes that are tens of feet in diameter, and these shapes are readily seen at the surface because of the mechanical distortion caused by the ice intrusion (Washburn 1980). The Pituffik Valley has a high occurrence of wedge ice and the probability is very high for its existence almost everywhere at the airfield. This extensive ice wedge polygon networks across the valley can be seen in Figure 6. Wedge ice does not exist in any man made fill at the Air Base.

Figure 5. Ice wedges excavated at Thule in the 1960s (CRREL photo). Ice wedges such as these, located under the runway, are the cause of many previous localized depressions on the runway. Depressions that currently exist at 62+00 and 70+00 were drilled in 2009 and wedge ice was found at the 6 ft depth.

Figure 6. Aerial photo prior to Air Base construction looking southwest. The polygonal ice wedge networks are seen to extensively cover much of the valley.

2.4.3 Segregated ice

If fine-grained soils exist with an ample supply of water, ice can continue to be created as *segregated* ice because of the wicking action of the fine-grained soils. This process creates near horizontal layers or lenses of ice, ranging from tenths of an inch to inches in thickness, and inches to feet in length. During sediment deposition, either glacial or fluvial, the soil particle size and amount of water available varied. Therefore, it is not uncommon to find very high ice content soils directly above, below, or adjacent to soils with lower ice content.

2.4.4 Relict ice

During glacial retreat, the margin of the ice sheet is dynamic, with glacial till being exposed and deposited, large volumes of water flowing off the ice sheet carrying outwash, and ice fracturing and being deposited on top and within loose piles of sediment. This fractured ice can be deposited and subsequently buried with sufficient expediency to prevent that ice from melting prior to permafrost creation. Therefore, chunks of ice, termed relict ice (Corte 1962), can exist within the permafrost. In the vicinity of the North River channel, the probability of relict ice surviving in the river terraces is relatively low because the river reworks the sediments.

2.4.5 Active layer

These are the near surface soils that undergo the annual process of thawing in the summer and complete refreezing during the winter. The bottom of the active layer is the top of the permafrost table. The depth of annual thaw depends on vegetative cover, soil type, soil moisture, and solar aspect (French 1976). In the Pituffik Valley, the active layer ranges from 1 ft deep in vegetated areas under a thick organic mat cover to 4 to 6 ft deep in unvegetated areas. It is very common to find a thick sequence of segregated ice at the base of the active layer. This is ascribable to the permafrost acting as an aquitard, and active layer water pooling at this location.

3 Airfield Construction

Construction of Thule Air Base began the summer of 1951 and, by season end, a 7000-ft penetration macadam runway was in service. By the summer of 1952, the runway was 10,000 ft long, with associated taxiways and ramps, all with a flexible asphalt pavement. The general pavement section as initially constructed consists of approximately 4 in. of bituminous pavement over a base course of poorly graded sandy gravels and gravelly sands to quarry rock, with up to 10% passing the no. 200 mesh. The material was obtained from either local borrow pits, giving rounded aggregate, or from quarrying operations around the area, using more angular material. The subgrade material is glacial till composed of silty, sandy gravel or silty, gravelly sand, 10 to 45% passing the no. 200 mesh, with very large cobble and boulders. The bedrock is diorite (ACFEL 1955).

3.1 Layout

The as-built plans (Appendix A) show that the runway alignment took advantage of the bedrock outcrop between stations 55+00 to 72+00. Large amounts of fill were then required to obtain minimum grade at the 08 and 26 ends of the runway and additional intermediate locations. The taxiways and ramps were located on higher ground of the lower elevations, such as around Lake Eddy. The runway is the highest embankment structure at the airfield, with exception of the extreme south end of the South Loop Taxiway. This design was optimal, serving three purposes: 1) founding of the runway on both bedrock and very thick embankments of fill, 2) taking advantage of lower regions for natural drainage and surface water storage, 3) locating embankments on higher ground, which is better drained and has relatively ice-poor soils. The South Loop Taxiway appears to have been purposefully constructed with minimal thaw-preventative fill, and in an area that obviously was very ice rich. This taxiway has been abandoned for at least three decades and it is unclear why it was constructed in this manner. It is interesting to note that Lake Eddy is visible in preconstruction photos and maps, as this had previously been thought to be man-made.

3.2 Considerations for permafrost

Owing to the continuous permafrost and massive ice conditions present, the base course fill thickness required to prevent heat energy from reach-

ing the permafrost table and inducing thaw was determined to be 6 ft (Metcalf & Eddy 1956). The 10,000-ft runway was constructed entirely on fill material, with the extreme ends of the runway requiring the greatest amounts, up to 30 ft. A portion of the runway, 1800 ft long, starting at station 50+50 and ending at 70+30, required excavation of a topographic high, resulting in a maximum cut at one location of 13 ft. The mid-point of the topographic high required excavation of diorite bedrock, and the rest of the cut section was excavated in frozen glacial till. The cut portion incorporated the 6 ft of thaw preventative fill as mentioned previously. However, because of design changes in the runway surface during construction, from a transverse slope to a crowned cross section, the resulting thickness from top of runway to bottom of excavation along the southern edge of the cut was reduced to only 3 ft (Fig. 7).

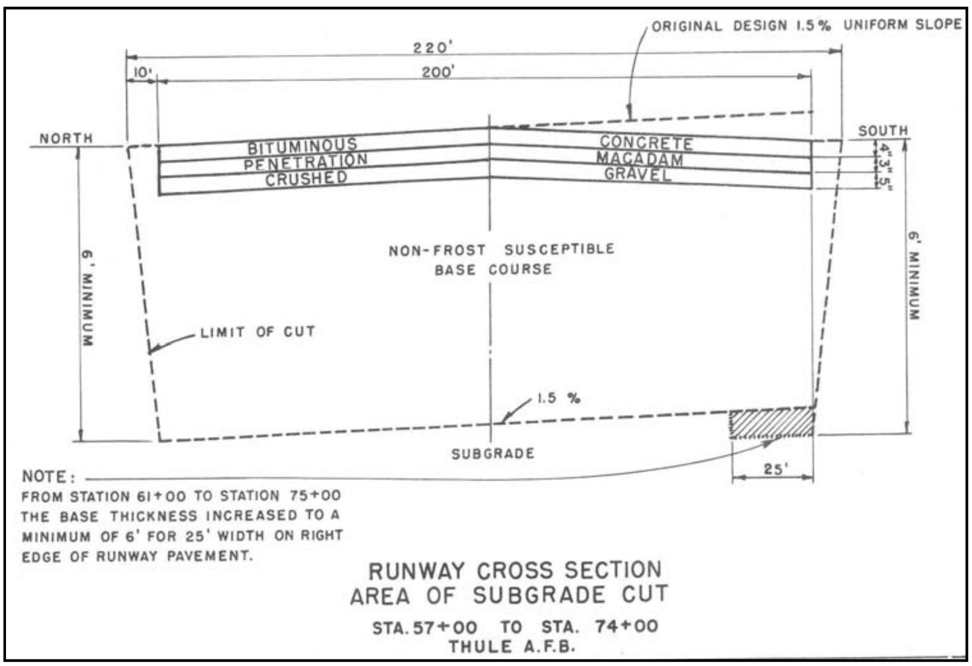

Figure 7. Cross section of the runway cut section from 57+00 to 74+00 showing initial design and mid-construction design change. The box excavation is also shown which was installed from 61+00 to 75+00 along the runway south limit (ACFEL 1955).

A releveling of the runway with an asphalt cement crown overlay, 60 to 90 ft wide, was completed in 1977, and in 1993 the asphalt cement of the runway was removed and reconstructed. Taxiway Alpha between Taxiway Charlie and the 26 end (west) received an asphalt overlay in 1977 and the remainder of the taxiways received asphalt overlays in either 1977 or 1993 (AFCESA 1996). Taxiway Alpha from the 08 end (west) to Taxiway Bravo was repaved in 2003 and from Taxiway Bravo to Taxiway Charlie in 2006.

The ramp from Base Ops (Bldg 619) to the Fire Station (Bldg 622) was repaved in 2003 and from the Fire Station to Hangar 7 in 2006.

3.2.1 Thaw settlement—fill thickness vs. box section

The Arctic Construction and Frost Effects Laboratory (ACFEL) conducted an investigation in 1953 and 1954 to determine the cause of thawing on the runway in the vicinity of existing Taxiway Charlie. Boreholes were drilled and pits hand dug to determine the subsurface conditions. Ice was found at a depth of 6.5 ft at subsidence location 58+00 (TR-5) and at 6 ft at subsidence location 72+00 (TR-7 in Fig. 8). Massive ice in the subgrade was thawing and causing differential settlement because of inadequate thickness of thaw-preventing fill in the runway. Measured thaw depths and numerical analysis conducted during this current study show that 8 to 9 ft of fill material should have been the design standard.

3.2.2 White pavement

Because of the low amount of thaw-preventing fill in the cut portion of the runway, the ACFEL investigation also looked at increasing the airfield asphalt albedo. Albedo is the ratio of reflected radiation to incoming radiation, with a perfect reflector having an albedo of 1.0. In the case of an asphalt pavement, raising the albedo would lower the temperature of the asphalt and reduce the heat energy introduced into the base course, in turn reducing the seasonal thaw depth. This has the potential to prevent thawing of the shallow massive ice and limit thaw degradation. ACFEL studied a 125-ft portion of the South Loop Taxiway, painting it white and instrumenting it to read soil temperatures at depth; this was also done for a non-painted area of the taxiway.

Plots of the depth of thaw under these two areas are compared for two seasons in Figures 9 and 10; the thaw depth was reduced by approximately 2 ft where the pavement was painted white. The thawing index for 1954 was greater than in 1953, but the deeper thaw in 1953 is attributed to heat introduction during excavation of the thermocouple strings, which were replaced in July 1953. Other investigators have confirmed these results (Berg and Aitken 1973). In a more recent study conducted at Kangerlussuuaq, Greenland, Jorgensen and Ingeman-Nielsen (2008) used ground-penetrating radar to measure 2.6 ft of decreased thaw depth under white painted asphalt

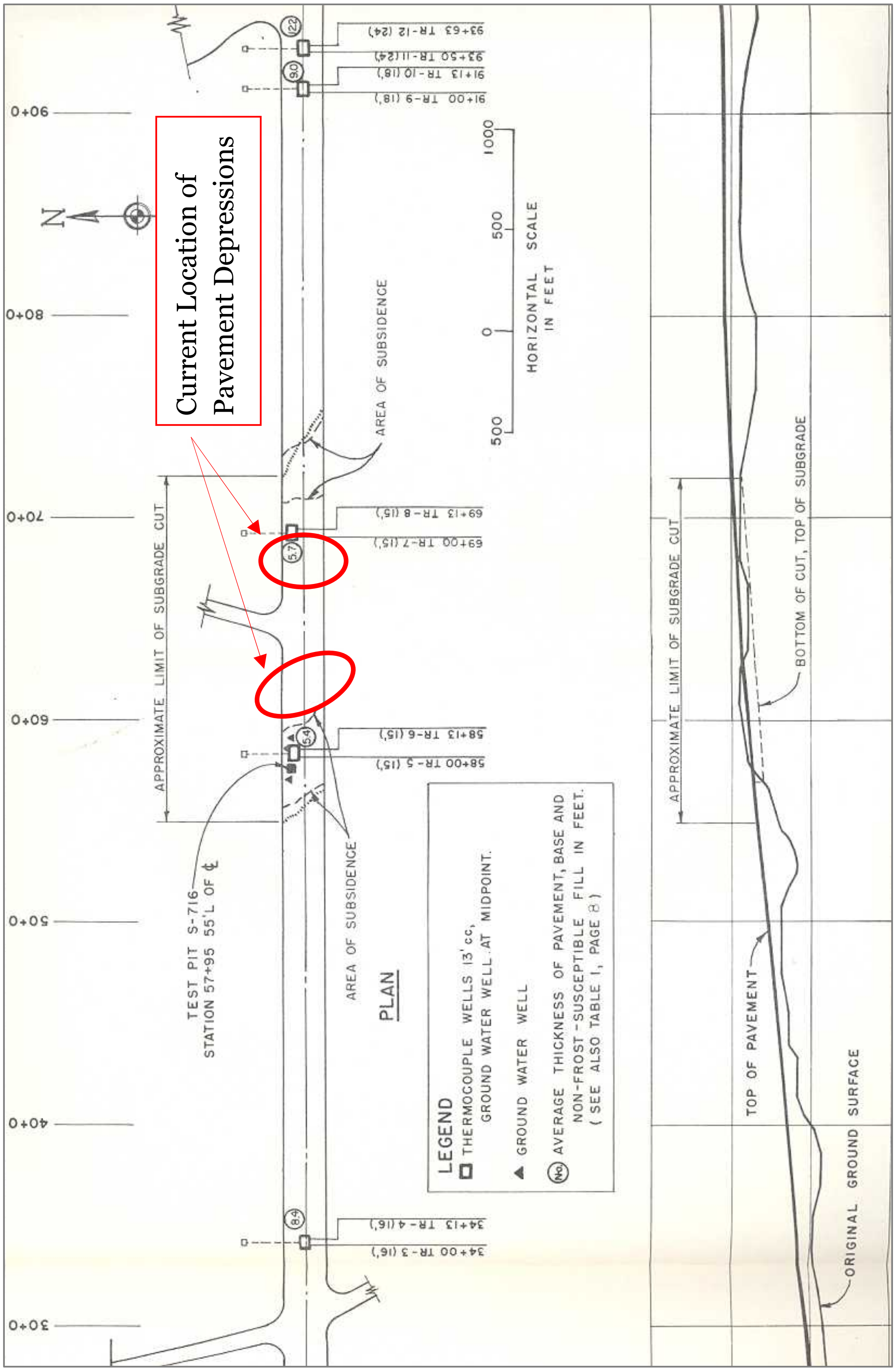

Figure 8. Plan view of depressions and test pits from ACFEL 1955 investigation (ACFEL 1955). Current depression areas are noted.

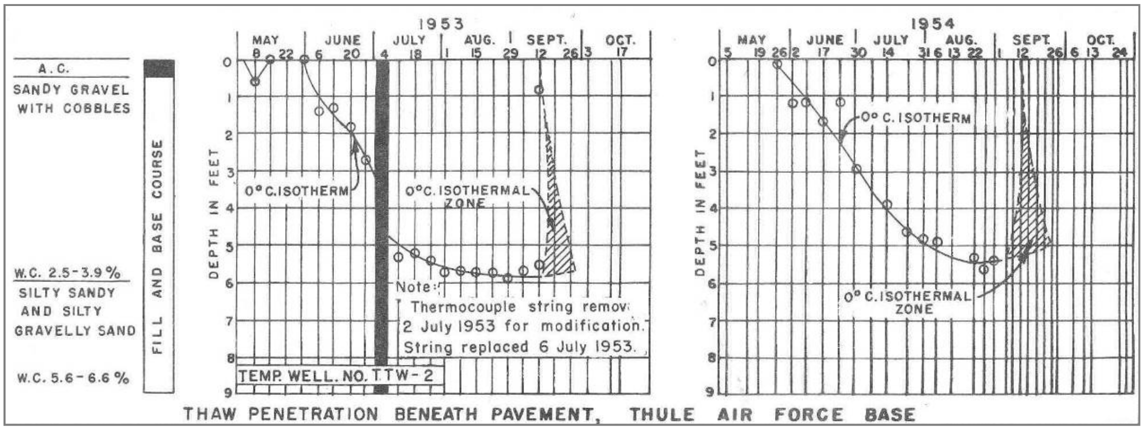

Figure 9. Temperature profile for two seasons under a white painted asphalt surface (ACFEL 1955). Although 1954 had a higher thaw index, the 1953 thaw depth is deeper owing to excavation for a new temperature measurement string.

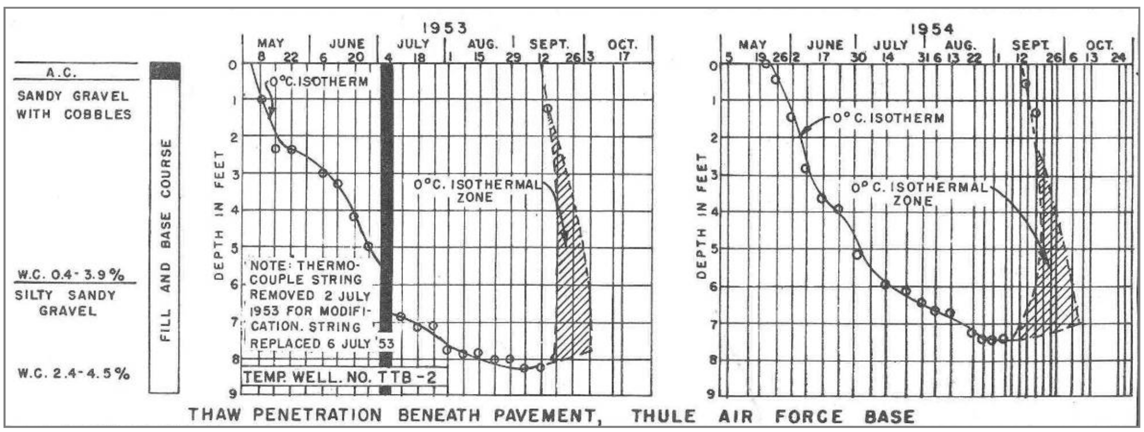

Figure 10. Temperature profile for two seasons under a non-painted asphalt surface (ACFEL 1955).

In 1957 a runway painting program was begun and by 1959 the runway and paved shoulders from stations 57+00 to 70+00 were painted white. In 1962 the runway from stations 20+00 to 80+00 was fully painted. The paved shoulders for their entire length and all taxiways and ramps north of the runway were painted. No documentation was found supporting or justifying the more extensive painting program from that of 1957. Berg (1976) suggested expansion of the painting program from 80+00 to 100+00 in an effort to decrease subsurface water flow on the 26 end (east) of the runway by raising of the permafrost table.

The painting is done on a rotating schedule, where the entire airfield will be painted once over 5 years. The runway receives special attention and may be repainted more frequently, depending on the condition and wear resistance of the paint. The painting causes the runway and taxiways to suffer from reduced friction between aircraft tires and the asphalt surface.

This reduction in friction reduces the braking ability of the aircraft, with rain events increasing the possibility for hydroplaning. Substantial increased operating costs are associated with the annual painting and daily maintenance.

The painted surface requires daily brooming in the winter because of the overnight growth of hoar frost. This is regardless of precipitation and is not noticed on black or natural asphalt surfaces. The development of hoar frost and the extreme slope, exceeding 2% grade, on Taxiway Alpha between Taxiway Charlie and the 26 end (east) of the runway initiates nose-wheel skip for some aircraft when taxiing. This section of taxiway has been suspected of major subsidence either from thawing permafrost or removal of fines by groundwater. This is false and is addressed in 3.3.

3.3 Airfield misconceptions

Over the course of this study, it has been noted that some anecdotal and literature information is inaccurate about permafrost and permafrost related issues. The most important to clarify are:

- The extreme slopes (exceeding 2% grade) at the east end of Taxiway Alpha are attributable to permafrost thaw:

    The slope that exists is the slope that was constructed in 1951 and can be verified with Metcalf & Eddy (1958) and AFCEC (1974).

- The water seen flowing through seeps, ditches, and culverts is melt water from permafrost thaw:

    It is estimated that nearly 100% of the permafrost around and under the airfield is at equilibrium with the current climate. There is no thaw degradation at any location around the airfield at a large enough scale to cause large amounts of melt water flow.

    Diurnal changes in water seepage and noticeable surface water flow is not from a diurnal starting and stopping of permafrost thaw. This is from diurnal changes in thawing ice in the active layer and diurnal changes in snow melt flow.

- During the summer the permafrost becomes softer and the bearing capacity is reduced of the subgrade:

    The permafrost remains frozen all year and because of this does not weaken for surface aircraft traffic in the summer. The active layer, or the seasonally freezing and thawing layer at the surface, will have greater bearing capacity in the winter when frozen than in the summer. However, the airfield is constructed of proper subgrade fill material per AFCEC (1974) and ACFEL (1955) and summer thaw would not create softer soil and sinking for aircraft.

- Thawing permafrost could cause large collapse of airfield soils such that the runway or taxiways could be rendered inoperable within days or hours:

    Thawing permafrost is a very slow and incremental process. It happens from the surface downward; therefore, no voids can be created below the thawing soils. Sudden collapse of soils in sink holes, such as can occur in Florida and Texas with limestone terrain, does not occur.

- Alligator cracking and block cracking is caused by permafrost:

    Airfield pavement fatigue resulting in different modes of cracking is mostly attributable to the extreme temperature changes experienced at Thule, and also the amount of soil moisture in the subgrade. Shallow permafrost will cause subsurface water to flow closer to the surface in the summer, and this effect would be most noticeable with white vs. black pavement.

4 Field Investigation

4.1 Test pits

During the field work of 2008, 12 test pits were excavated. The pits were strategically located to 1) investigate the depth of seasonal thaw (depth to permafrost) under white and natural black pavement, 2) investigate the source of the surface depressions, and 3) investigate the subsurface at groundwater seeps. Most importantly, massive ice at the depth of the permafrost was discovered in nearly all the depressions excavated (Fig. 11). The depressions were similar in size and shape to the depressions found currently in the runway at 62+00, approximately 4 to 5 ft long, up to 3 ft wide, and with varying depths from inches to over 2 ft. The ice encountered was most probably wedge ice, and this longitudinal geometry is consistent with that assumption.

Figure 11. Test pit near Taxiway Bravo Extension. Wedge ice is seen at 5.5 ft depth.

4.2 Borehole drilling

During the field work of 2009, 84 subsurface boreholes were drilled in areas mostly on and around the runway. Direct push technology (DPT) drilling, which uses a high frequency hammer to pound a 2.25-in. × 5.0-ft long barrel into the ground, was used. This system was ideal for testing areas in the runway and shoulder without overly disturbing the pavement surface.

The coarse sediment permafrost of the Thule area generally limited the penetration to less than 10 ft. If massive ice was encountered, it would generally be at the depth of the bottom of seasonal frost and the permafrost table, so deeper penetration was not required. Again, the important discovery from this work was that nearly all depressions drilled in the runway, taxiways, and shoulders were found to have massive ice at the depth of the seasonal frost. This coincides with the information gathered from the test pits. The ice encountered in most of the boreholes was most probably wedge ice. The ice found in the borehole in the North Shoulder near 40+00 and the borehole at runway centerline 77+75 was most probably segregated ice, from active layer water as these locations are over very thick fill, where ice-rich permafrost soils are very deep. The specific borehole information can be found in Bjella (2010), and a summary table of drill information is located in Appendix B of this report. Additionally, a systematic drilling program was conducted at areas exhibiting no thaw depressions. No massive ice was encountered in these borings, which provides further evidence that the depressions are the result of thawing massive ice, and that massive ice does not exist everywhere under the airfield; it is co-located with with thawing areas.

Significantly, the drilling found only five boreholes on the active runway surface that encountered ice (Table 2).

Table 2. Boreholes that encountered ice. Boreholes in the runway are in red.

Borehole no.	Location	Description
47	58+35	North of N. paved shoulder in outfield
1,4	59+00	North of N. paved shoulder in outfield
34–41	59+00	S. paved shoulder
48	60+30	N. paved shoulder
5, 6, 7,	62+00	Active runway between edge lighting
51, 52,53	62+70	N. paved shoulder
49	66+75	Active runway centerline, deep at 9’
76	Txwy A	lowpoint of the big dip near the culvert
77, 78, 79	Txwy A	Entrance from the Txwy to the CP 2&3
72	S.L. Txwy	S. Loop Txwy and S.E. Loop Txwy

4.3 Geophysics

Non-destructive, surface based geophysical methods have been used during every phase of this investigation (Bjella 2008, 2010): ground penetrating radar (GPR) and capacitive coupled electrical earth resistivity (CCER) measurements were the primary methods. The GPR is useful for imaging the subsurface, especially when nearly horizontal layers of materials are present, such as the native surfaces and layering of engineering fill. Water and ice possess differing dielectric constants, providing good contrast for imaging depth of seasonal frost. Also, native soils and bedrock provide good contrast when compared with frozen soil and allow for imaging the depth of these units. The CCER is useful for imaging large subsurface areas that have higher ice content vs. low ice content or are frozen vs. thawed. Wedge ice is difficult to survey with any method, unfortunately, because of its relatively small size compared to the array size and electrical frequency of the instrumentation.

Over 50 miles of geophysical surveys have been conducted. Most importantly, the deep GPR images have provided collaborating evidence to the subsurface topography provided in as-built drawings of the airfield. These data validate the subsurface terrain model used to prescribe thaw mitigation measures.

4.4 Painting frequency and effectiveness and albedo measurements

There is a perception that the airfield has been entirely and pristinely white since the painting was prescribed in the late 1950s. However, a review of the pertinent literature and historical photography suggests otherwise. As mentioned previously, the white painting of the runway and shoulders began in 1957 from 57+00 to 70+00, and was extended to include full width painting from 20+00 to 80+00 in 1962, with the 2000 ft at either end maintained as a natural asphalt color (Fig. 12 and 13). No information was found suggesting thaw depression development in these areas. Sometime after 1976 and to the present, the full airfield, including the full length and width of the runway, the taxiways, and the ramps, has been painted, but on a schedule that rotates about the airfield on a cycle of 3 to 5 years. Because of this, the historical and contemporary photography illustrates times when paint was extremely faded before reapplication (Fig. 14 to 17).

Figure 12. Airfield in September 1975 showing the extent of painting up to that time. The landing zones, 2000 ft from either end of the runway, are not painted nor is the 26 or 08 ends of Taxiway Alpha. This study found there was no information anecdotally, or in the literature, suggesting past thaw depression problems in these areas (Funder 1990).

Figure 13. Undated photo of airfield showing extent of painting prior to 1976.

Figure 14. Undated photo of the airfield obtained from Thule personnel. The painting is in process during this photo. It is unknown if the dark pavement from approx. 50+00 to 100+00 is from wear or if milling or some other program is being conducted.

Figure 15. View from the tower April 2011, looking east to the 26 end of the runway. The faded and dark nature of the paint is very evident against the backdrop of white snow.

Figure 16. View from the tower in April 2011, looking directly south over Lake Eddy. The dark colored runway and taxiway are visible.

Figure 17. View from the Tower in April 2011, looking southwest to the 08 end of the runway. The dark colored runway and taxiways is visible.

Most importantly, in 2008, the runway was milled 15 ft either side of the centerline to remove excessive layers of paint and regain micro-texture for aircraft safety. To prevent the reoccurrence of excessive paint along this “keel” section, only a light “white-wash” coat of paint has been applied to this milled centerline. In 2009 the milling and white wash painting was extended to 50 ft either side of centerline. Because of winter maintenance to ensure aircraft safety, this white-wash coat is unintentionally removed by brooming, and, by the beginning of the following warm season, this keel is nearly natural asphalt black until early to mid-August when the white-

wash is reapplied (Fig. 18). Therefore, since summer 2009, the runway has had virtually no white paint along this 100-ft-wide keel during the crucial solar heating months of June, July, and early August. No thaw depressions have been created during this time, and the existing thaw depressions (namely at 62+00) have not increased in size or depth. This is especially enlightening because the summers of 2008, 2009, and 2011 were the fifth, third, and fourth warmest summers, respectively, on record since 1951 (Table 1).

Figure 18. View of the 26 end of the runway April 2011. The winter maintenance has removed the white wash coating applied the previous summer. This state persists through the warm period of June, July and early August before repainting.

The albedo of various stages of painting of the airfield asphalt was measured in July 2011. The reflective ability of a pavement is not only a function of the color, but, to a lesser degree, is also a function of the roughness, where smoother surfaces reflect more radiation. We used a Kipp & Zonen solar radiation albedometer mounted on a 5-ft rod that could be held beyond arm's length to eliminate incident reflection from the operator. The airfield area where Taxiway Alpha turns south to join with the 08 end (west) of the runway was chosen as a primary location to calibrate the albedometer to the depth of thaw. This area has multiple stages of painting, no paint, and bare soil that could be measured. Other areas measured are where Taxiway Alpha connects to Taxiway Charlie, where Taxiway Alpha connects to the 26 end (east) end of the runway, where Taxiway Bravo Extension connects to South Loop Taxiway, which has a transition from white paint to natural black surface, and the various stages of painted surface on the runway at 91+00.

GPR was used to measure the thaw depth for the various albedos. As noted previously, GPR works very well for dielectrically contrasting horizontal reflectors. During summer measurements, thawed, wet material of the active layer overlies the frozen permafrost soils. It is possible to obtain relatively accurate measurements of depth by surveying with GPR a known object in the subsurface at a known depth and then calibrating the GPR parameters to this known object. This was done on Taxiway Bravo, where the culvert draining Lake Eddy crosses the taxiway. The culvert depth was measurable from the side of the taxiway embankment. The GPR measuring of active layer depth was confirmed during test pit excavation and borehole drilling and is good to ± 0.25 ft. The albedo values are shown in Table 3 and are plotted in Figure 19. This relationship is linear and, for the brightest of paint, the albedo approaches to 0.60 with the thaw depth being near 4 ft, while the natural black surfaces approach 0.12 with thaw depth of 6.5 ft. This white vs. black difference in thaw depth coincides with the ACFEL study of 1953, where over 2 ft of thaw reduction was measured. Photos of the various stages of paint measured for albedo are shown in Figures 20 to 23.

Table 3. Albedo measurements, measured depths, and locations.

Location	Thaw depth (ft)	Albedo	Paint description
91+00	3.9	0.58	Fresh paint bright keel
Txwy B Ext	5.1	0.44	Old nearly intact white paint
Vortac Calib	5.3	0.26	Newer paint now brushed and faded
Txwy B Ext	6.5	0.15	Never painted
Txwy A at Txwy C	5.3	0.32	Faded due to brushing
Txwy A-08 end	4.0	0.61	East side of Txwy A—bright but older
Txwy A-08 end	4.8	0.51	West Bright (but old with some missing spots)
Txwy A-08 end	5.4	0.30	Faded white with much missing
Txwy A-08 end	5.9	0.13	Milled to black
Txwy A-08 end	6.6	0.12	Dirt

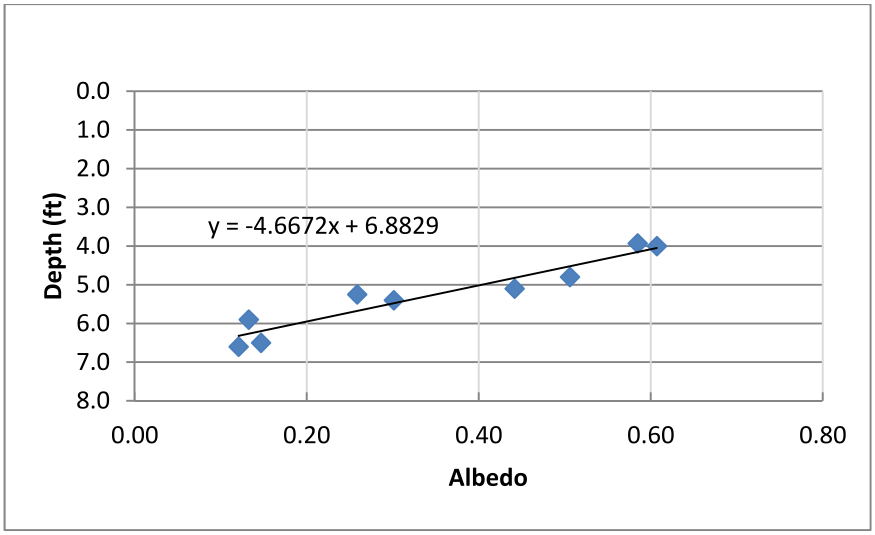

Figure 19. Albedo vs. thaw depth.

Figure 20. Bright white runway at 91+00. Albedo measured at 0.58 and the thaw depth measured at 3.9 ft.

Figure 21. Brushed and faded milled surface on Txwy A at Vortac Calibration. Albedo measured at 0.26 and thaw depth measured at 5.3 ft.

Figure 22. View east along Txwy A at Txwy Charlie. Albedo measured at 0.32. The measured thaw depth is 5.3 ft.

Figure 23. Old white paint transitioning to never painted surface at Txwy Bravo Extension. The white albedo measured 0.44 and the thaw depth measured 5.1 ft, while the black surface measured 0.15 and the thaw depth measured 6.5 ft.

The airfield has not always been fully veneered by the white paint. Areas have either not been protected by paint for the full time since painting was prescribed in the late 1950's, or the paint has been allowed to fade. More recently, it has been removed almost entirely for full solar impact. The albedo and thaw depth measurements demonstrate that the effectiveness of the white paint, if in pristine condition, can reduce thaw depth up to 2.5 ft. If the white paint is slightly faded, removed, or the area includes patches of dark colors among bright white, the albedo is greatly reduced and the thaw depth mitigation loses up to 50% of its effectiveness. The areas of the runway keel and taxiways where the previous season's paint is nearly completely removed the following winter experience almost no albedo mitigation. For the last three summers, the runway has effectively had no thaw mitigation along the entire length and a width of 100 ft. No thaw depressions have developed, and the existing thaw depressions at 62+00 have not increased in depth or extent.

4.5 Insulation test

An alternative to painting the airfield where thaw depth reduction will be required is to install extruded polystyrene insulation (XPS—rigid board insulation) below the asphalt to resist the penetration of heat energy. This concept has been successful for many cold regions engineering projects for the last 40+ years (Cheng et al. 2004; Esch 1986; U.S. Army 1984). The XPS sheets are laid horizontally, side-by-side, and at an appropriate depth,

depending on the situation. The effect of the insulation was modeled with one-dimensional and two-dimensional thermal solutions; these demonstrated that, for gross determinations, this would be a very satisfactory solution.

The thermal modeling parameters, such as the thermal conductivity and volumetric heat capacity, are functions of soil moisture content. Soil moisture can vary within short distances in the real environment; therefore, these thermal values are generally assumed, and averaged to obtain a more general solution for a project location. Because of this, it is possible that variations may occur in these numeric solutions that can have unintended consequences. For example, the numeric solutions might suggest 2 in. of XPS thickness will be sufficient, when in actuality, owing to the variance in soil condition, 4 in. of XPS thickness will be required to ensure the required effect.

For this reason, an insulation test embankment was created at the gravel pit area of Larsen's Square east of the Air Base during the summer of 2010 to ascertain the true effect of XPS in that environment and for that soil type. The embankment consists of three test sections: a 4-in.-thick XPS section, a 2-in.-thick XPS section, and a control section with no insulation. The sandy gravel surface where the embankment was constructed was first leveled by excavating down 1 ft; XPS was then laid at that level and gravel material of less than 1.5 in. diameter was placed in 12-in. lifts and compacted with a walk-behind 400-lb plate compactor. The overall dimensions of the three side-by-side test sections are 60 ft long, 20 ft wide, and 4 ft of fill over the XPS, and 6 ft of fill in the control section (Fig. 24).

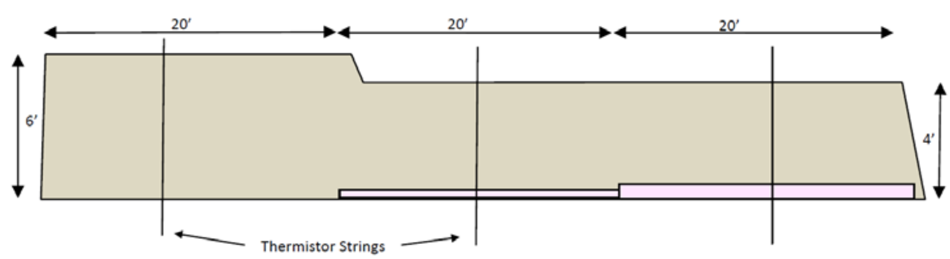

Figure 24. Cross-section of the insulation test embankment.

To minimize the thermal edge effects, an uncompacted fill buffer was placed around the entire test embankment measuring over 10 ft wide and 7.0 ft high. The buffer was placed by end-dumping loads of unscreened gravel material. The crests of the dump piles were then pushed to fill the

valleys between the piles, resulting in a roughly flat buffer at least 3 ft higher in elevation than the surface of the test embankment (Fig. 25 and 26). Temperature measurement strings were installed in each test section to gather information with a data logging system. The sensors are located at 1-ft intervals, with 4-in. spacing of the sensors on either side of the ridged board insulation. The embankment had the opportunity to completely freeze during the winter of 2010–2011, and temperatures were downloaded in April of 2011 and September of 2011 to ascertain performance. Plots of the temperatures vs. depth are shown in Figures 27 and 28.

Figure 25. XPS insulation placed at base level for the test embankment.

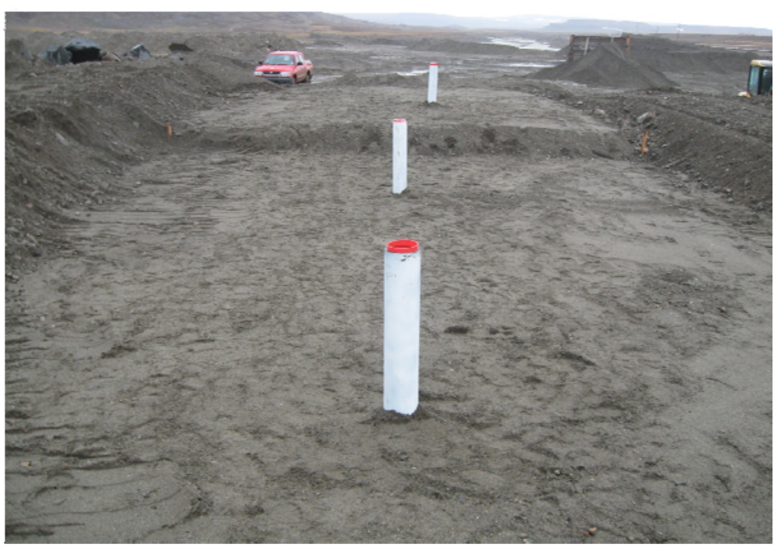

Figure 26. Completed test embankment with thermal buffer fill piled around the test.

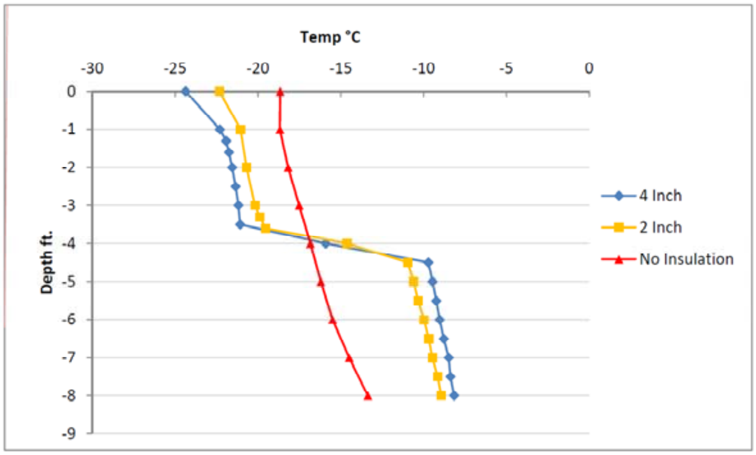

Figure 27. Insulation test measurement 1 April 2011. This plot demonstrates the thermal offset provided by 2- and 4-in. XPS insulation when the air is colder than the deeper subsurface.

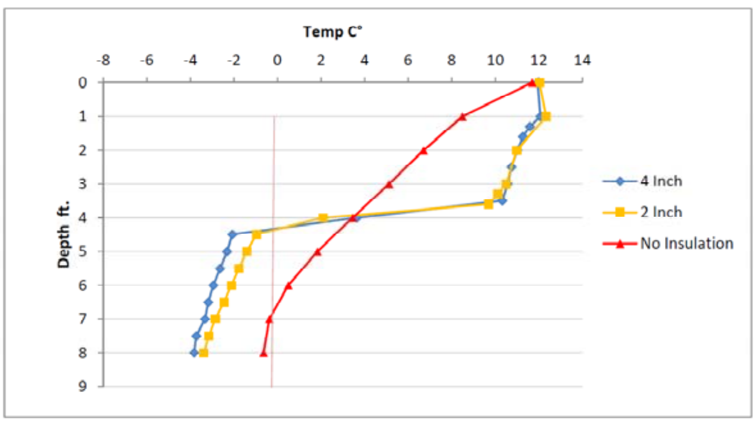

Figure 28. Insulation test measurement on 6 August 2011. This plot demonstrates the thermal offset provided by 2- and 4-in. XPS insulation when the air is warmer than the subsurface. The ultimate frost depth was held at the depth of the insulation. The summer of 2011 was the fourth warmest average air temperature recorded at the Air Base.

4.6 Subsurface temperature measurement

Three soil temperature measurement stations were installed in 2009. The stations consist of a string of thermistors at 1-ft intervals, starting at the surface; the string is installed in a ¾-in. inside diameter PVC pipe closed at the bottom. The pipe was then backfilled with 10-20 silica sand. All three sites are connected to data logger systems for year round measurement. The first station is located in a cluster pit off the South Loop Taxiway between the runway and the SAC Ramp. This location is the "Black Pavement" site designed to measure the temperature under a representa-

tive portion of natural colored pavement. The second site, "White Pavement," is located at the very southern edge of the SAC Ramp in a white painted area. The third site, "Outfield," is located in bare soil fill material between the firehouse and the Terminal Operations Building. Plots are presented in Figures 29–31, and were taken at or very near to the maximum depth of thaw for 2011.

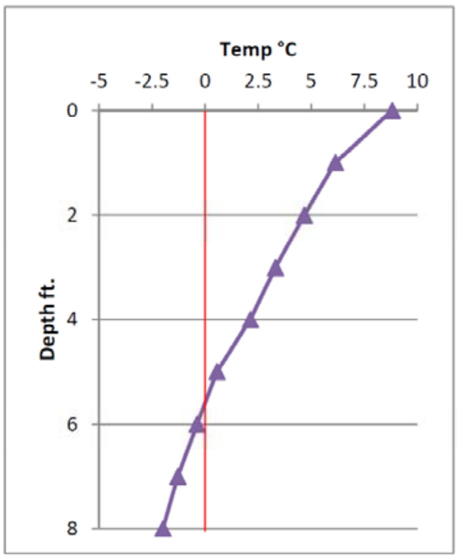

Figure 29. Subsurface temperatures measured at the "White Pavement" site. Measurement taken 11 August 2011 is the deepest thaw obtained for that summer. The albedo was 0.32 and the depth is almost 5.5 ft. This is consistent with the albedo vs. thaw depth presented in this report.

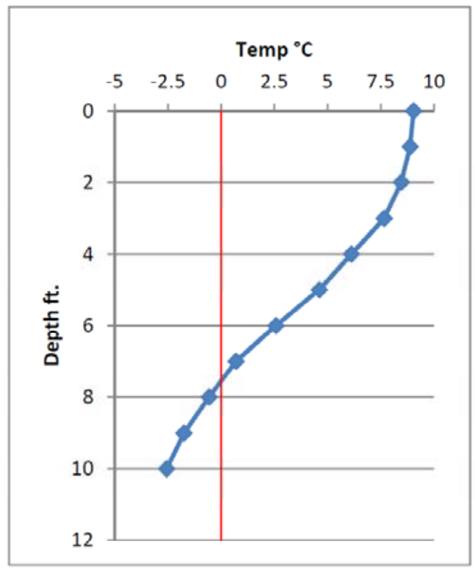

Figure 30. Subsurface temperatures measured at "Black Pavement" site. Measurement taken 11 August 2011 and is deepest thaw obtained for that summer, almost 7.5 ft, which is approximately 1 ft deeper than other measurements in natural colored pavement.

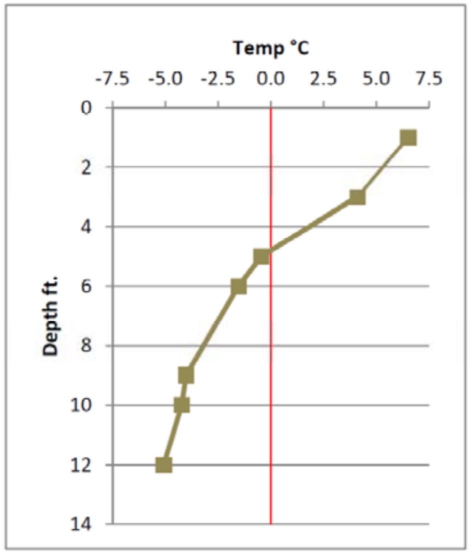

Figure 31. Subsurface temperatures at a permanent station in fill material near the Terminal Operations Building. Measurement was 1 August 2011 and is deepest the thaw obtained for that summer, almost 5 ft, which is consistent with borehole and test pit investigations, and the albedo vs. thaw depth measurements in fill material.

5 DISCUSSION

Permafrost affected terrain can be complicated to assess when considering its effect on engineering structures. Large ice masses in the form of wedge and segregated ice are generally the main features of concern and are difficult to detect unless there is some form of surface expression, or without an extensive and expensive drilling campaign. Because of this, a permafrost terrain model was created for the airfield, via the literature—photos—and the measured data, to visualize the native permafrost terrain as it existed prior to construction. This model was then compared to reported problems and was used to determine alternative ways to mitigate those issues. In the end, the model allows for an uncomplicated way to visualize permafrost across the airfield.

5.1 Permafrost terrain model

A conservative view of the airfield's permafrost situation would be to assume that thaw-unstable (ice rich) permafrost exists at some constant shallow depth below the entire airfield complex. This perspective assumes that a structure placed at one location would be subjected to the same natural parameters as another location, even if they are thousands of feet apart. The white painting of the airfield follows this viewpoint: nearly 100% of the active airfield facility is or has been painted white at some time. However, observation of the airfield, the drilling and excavation of the thaw depressions, and permafrost engineering experience tell us that the vulnerable locations for thaw degradation are where wedge ice is located in the native permafrost soils. This does not suggest that there will be no thaw settlement in ice-rich soils where only excess matrix ice or segregation ice exists; however, for the airfield in general, the most critical locations are where wedge ice exists.

The engineering design specified in 1951 was to place a minimum of 6 ft of fill over the native surface to act as insulation against thawing of the massive ice. We now know that the 6 ft of fill was inadequate (Fig. 32). The *thaw-critical interval* is defined as the space below the surface that is between the current thaw depth at approximately 6 ft and the possible thaw depth attainable without thaw mitigation. It includes an increase in average mean annual air temperature (MAAT) of +2°F, or a maximum thaw depth of 9 ft.

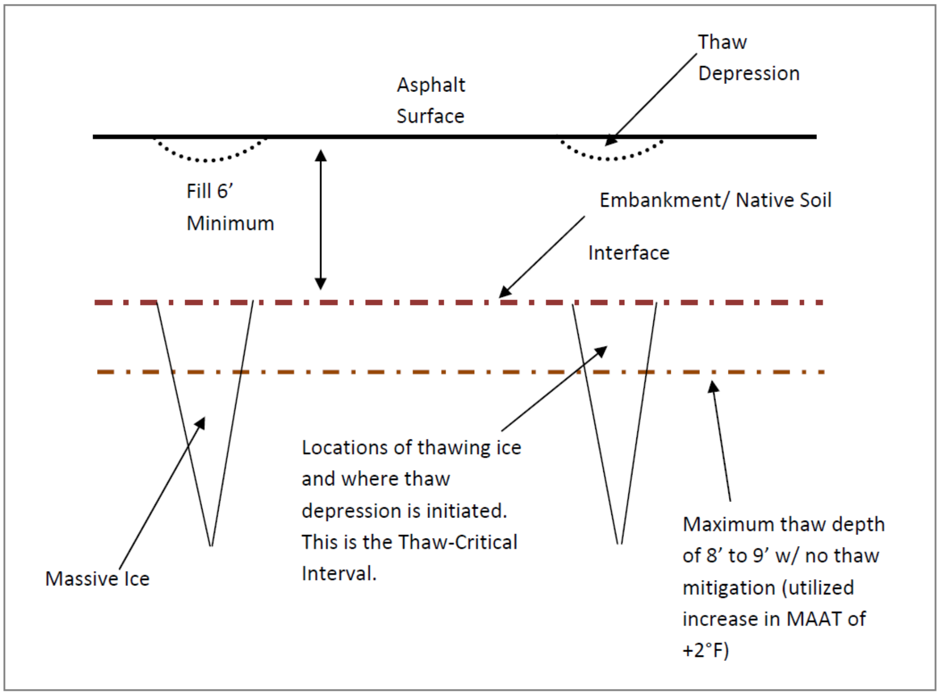

Figure 32. Simplified physical situation causing thaw depression on and around the airfield. The fill section is inadequate to prevent summer heat energy from reaching the depth of massive ice. The thawing ice creates a void that is filled with adjoining soil and a surface depression is the end result.

Figure 32 shows that when the thaw front extends down into the massive ice, causing thaw, the surrounding soil fills that void, causing a subsequent surface depression to develop. *If the heat energy can be stopped from penetrating to the depth where settlement initiates, thaw settlement will also stop*. When thaw degradation happened at a particular location, the massive ice was thawed to that depth and depressions developed. The damage has been done because ice has been removed during the initial thaw and the depression at the surface has long since been repaired with subsequent repaving. The thaw depth would be no deeper unless a significant warming in the summer heat regime occurs. Only such an increase in heat energy could initiate thaw degradation again as the thaw depth increases into previously unthawed massive ice.

If the generalized view shown in Figure 32 existed across the entire airfield, thaw depressions would be developing everywhere; however, this is not happening. The initial investigation made it evident that the airfield should not respond equally at all locations to a change in the thermal regime. The foremost reason is that an undulating topography existed prior to the construction of the airfield. The topography overall slopes down-

ward from east to west, and this undulating surface required low areas to be filled, and high areas to be cut. Most of the fill areas have more than adequate amounts of material to prevent heat energy from reaching the ice-rich native soils, but in the areas that were excavated (cut), the 6-ft-high fill surface was placed closer to ice rich native soils. So, what was the original topography? How did the design alter that topography? What is the end result for the thermal and structural stability?

The ACFEL (1955) report specifically shows thaw degradation at the 57+00 and 70+00 locations on the runway, but no place else. It also provides a simple illustration of subsurface topography that supposedly existed prior to construction, suggesting that most of the runway embankment required more fill than the 6 ft specified (Fig. 8). It also shows that a cut section was required to make grade from approximately 57+00 to 70+00, and the margins of this cut coincide with the depressions shown at 57+00 and 70+00. Two other reports specified the subsurface topography before construction. The AFCEC (1974) *Pavement Evaluation* report (Fig. 33), and the Metcalf & Eddy (1958) drainage study report (Fig. 34 and 35). There was little similarity among these three as-built drawings, with the exception of the cut area at 57+00 to 70+00. So at least one of the as-built plans needed to be validated if possible.

Ground penetrating radar was used to determine which as-built was correct. The GPR provided continuous, deep visualization of the subsurface, allowing a high degree of correlation with the as-built plans of the Metcalf & Eddy report (examples are shown in Fig. 34 and 35). These plans (Appendix A) present six cut sections between 0+00 and 100+00.

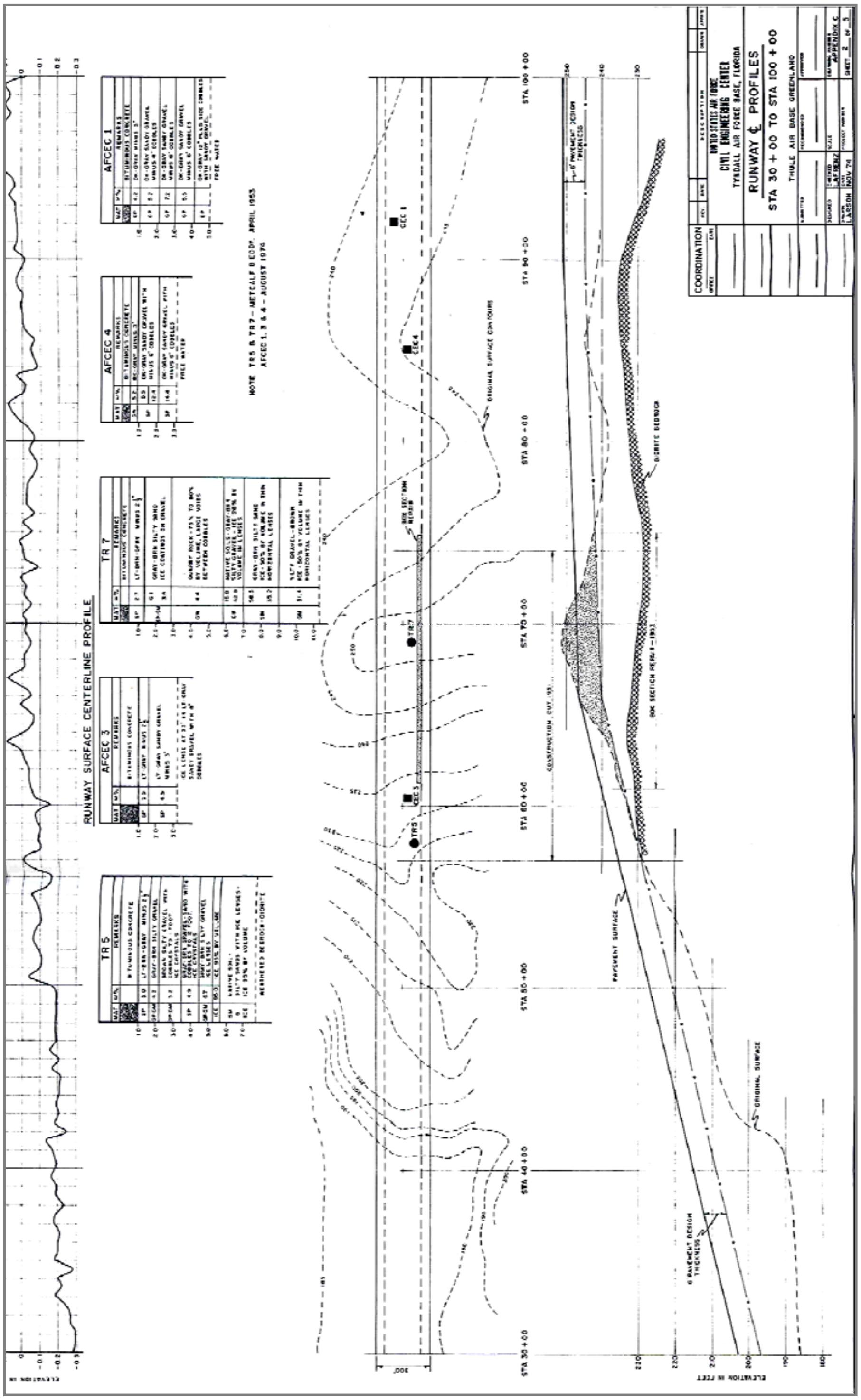

Figure 33. As-built plan provided in the AFCEC (1974) *Pavement Evaluation* report. The original surface before airfield construction is shown and is similar to the ACFEL (1955) report. These differ from the Metcalf & Eddy 1958 drainage report, which shows six cut sections.

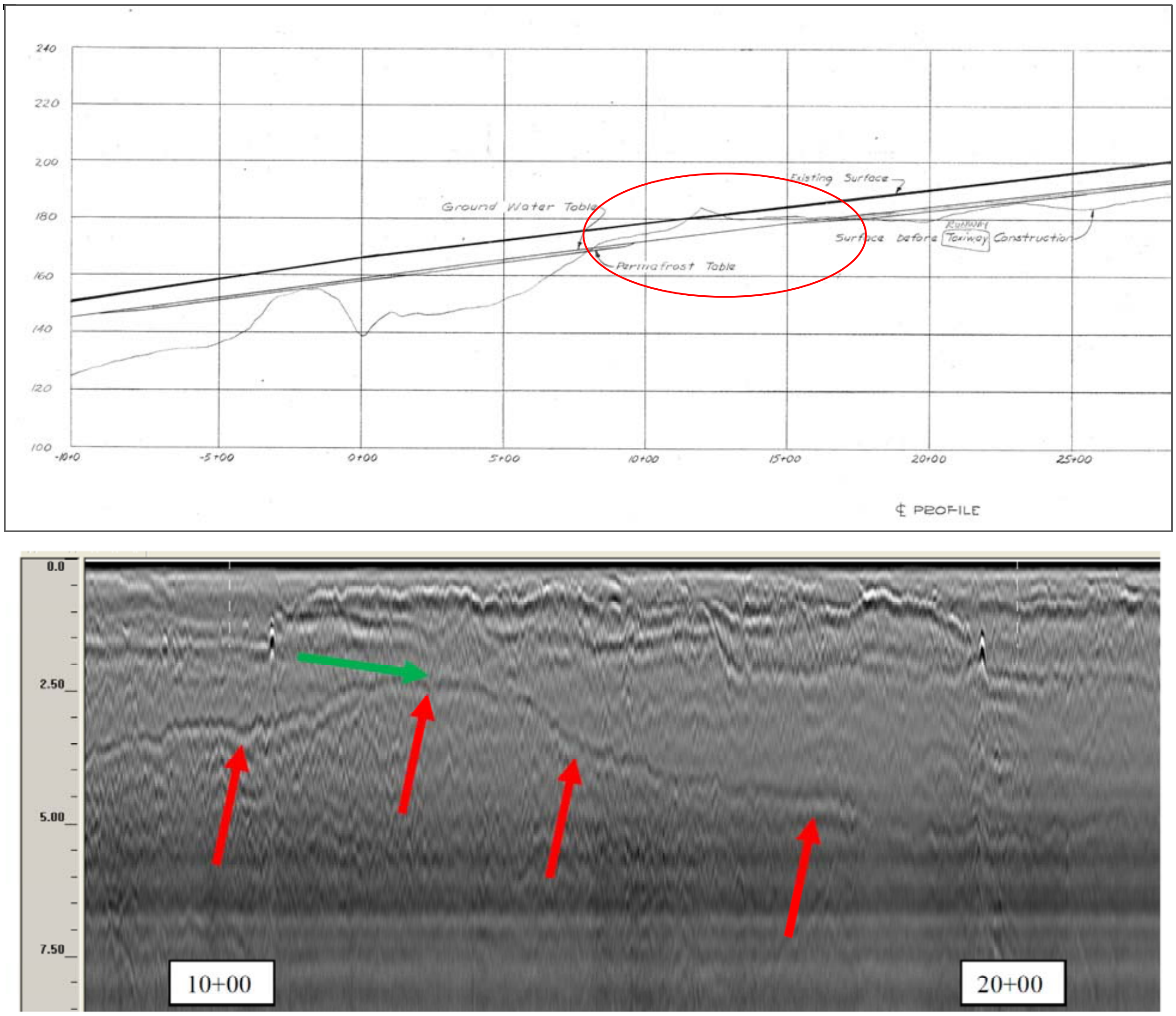

Figure 34. Top: a portion of the runway as-built provided by Metcalf & Eddy. A cut section is shown starting at 5+00 and ending at 17+00. The red oval indicates the location shown in the GPR image in the bottom figure, a portion of a radargram showing the subsurface between 8+00 and 22+00. Survey was taken on the right side of the runway between the centerline and the edge lighting. The rise in topography shown in top drawing is clearly seen at the red arrows. Green arrow indicates location where near surface ice-rich soil may exist at 8.2 ft depth.

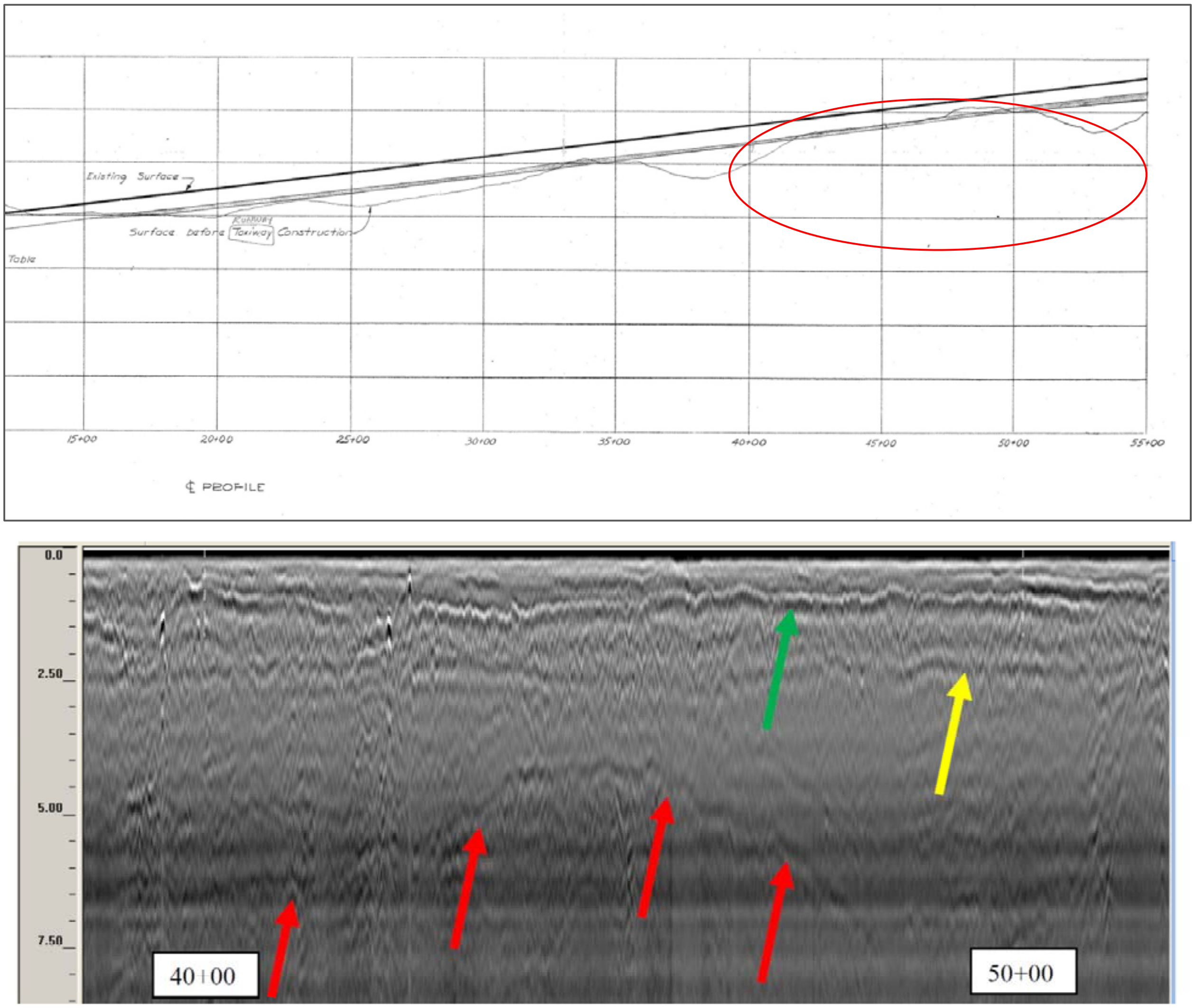

Figure 35. Top: portion of the runway as-built provided by Metcalf & Eddy. A cut section and near-cut section are shown starting at 42+00 and ending at 51+00. The red oval indicates the cut section shown in the bottom figure, a portion of a radargram showing the subsurface between 38+00 and 52+00. This survey was taken on the right side of the runway between the centerline and the edge lighting. The rise in topography shown in the top figure is marked by red arrows. The transitions to multiple lifts of coarser material for the asphalt base course (Fig. 7) are shown by the yellow arrow starting at approximately 8.0 ft. The green arrow indicates a visible strong reflector at the 3-ft depth and this most probably corresponds to the bottom extent of the 1992 repaving subgrade reworking.

With the base level topology understood, the surface and near-surface frozen sediment section could be constructed in the model. We know that a layer of glacio-fluvial sediment overlies the bedrock in the Pituffik Valley, and that these are host to the massive ice, mostly in the form of wedge ice. Historical aerial photographs were reviewed to get an idea of how the terrain appeared prior to construction, and one image in particular shows that a moderately dense ice wedge network (20 to 30%) was extensive across the valley (Fig. 6). Because the sediments are of relatively young age

(late Pleistocene–early Holocene) and epigenetically frozen, it is assumed the massive ice occurs from the surface down 10 to 15 ft into the sediments. Locally, the wedge ice is much shallower where bedrock is shallow. This was confirmed with the field investigation.

The model is completed with the addition of the accurate cut-and-fill thicknesses over the top of the ice rich native soils. The cut and fill locations indicate where the massive ice and ice-rich soils may be close to the surface and in danger of thaw. As the fill thickness decreases, the native ice-rich terrain surface becomes closer to the man-made surface, within the thaw critical interval. Figure 36 illustrates this general concept. Therefore, if the cut was not substantially deep enough to excavate the entire near surface wedge ice, thaw danger is possible at the margins and surface of the cut areas. However, it is possible that, in some of the cut areas, where shallow bedrock existed, the massive ice was completely removed.

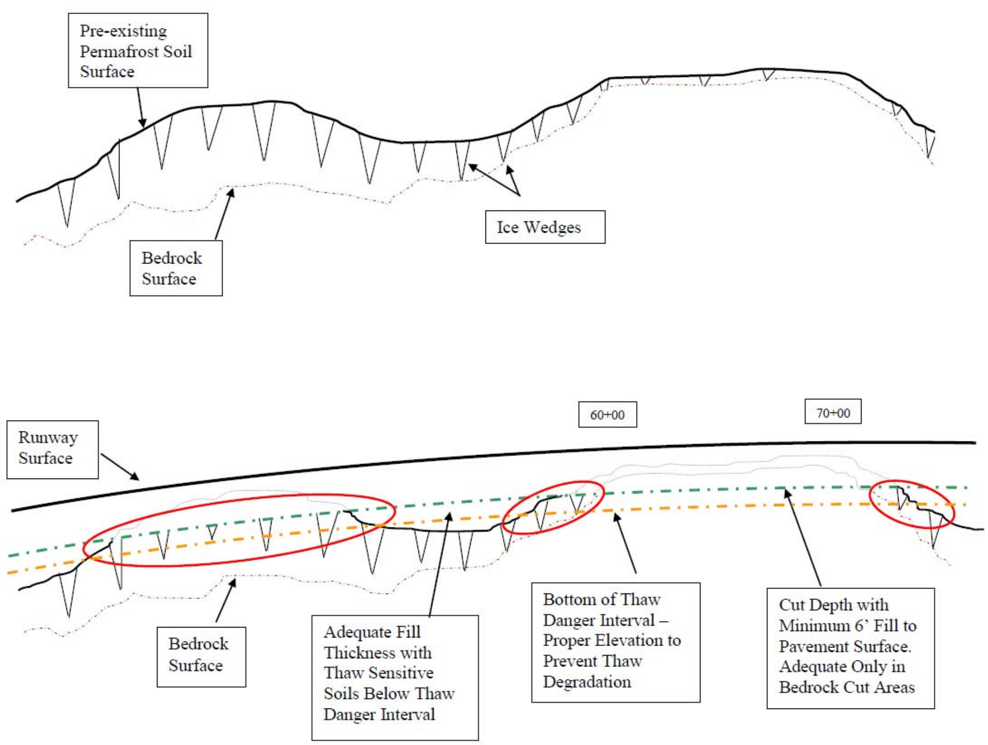

Figure 36. Permafrost terrain conceptual model created for the airfield.

5.2 Areas requiring thaw monitoring and mitigation, or both

The Metcalf & Eddy (1958) as-built drawing can be used to visualize the cut and fill sections for the airfield, and, because of this we can discretely

look at the airfield in cross-section, to compare these cut and fill sections to current and past depressions, and to determine which areas are in need of possible thaw mitigation. The past depressions are taken from Metcalf & Eddy (1958) and ACFEL (1955). Table 4 breaks the airfield down into cut and fill sections, describes those sections in terms of a thaw critical ranking, and correlates these areas with known depressions that either exist today, or have existed in the past. Table 5 describes the critical sections in greater detail.

Table 4. Listing of the runway areas by cut and fill sections.

Section	Cut or fill	Description	Previous or existing depressions	Thaw Critical Ranking
-10+00 to -3+00	Fill	Thick, over 20 ft	No	No
-3+00 to -1+00	Fill	Shallow, less than 5 ft	No	No
-1+00 to 8+00	Fill	Thick, over 15 ft	No	No
8+00 to 17+00	Cut	3–4 ft cut for 70%, 6–8 ft for 30%	Yes	Marginal
17+00 to 22+00	Fill	Shallow, 5–6 ft	No	No
22+00 to 24+00	Fill	Shallow, less than 3 ft	No	Low
24+00 to 33+00	Fill	Thick, over 6 ft	No	No
33+00 to 35+00	Cut	Shallow, less than 2–3 ft	No	Low
35+00 to 42+00	Fill	Thick, over 10 ft	No	No
42+00 to 52+00	Cut	2–3 ft for 70%, 3–4 ft for 30%	Yes	Marginal
52+00 to 56+00	Fill	Thick, over 10 ft	No	No
56+00 to 64+00	Cut	Deep, over 12 ft	Yes	High
64+00 to 67+00	Cut	Shallow, 2–3 ft	Yes	Marginal
67+00 to 74+00	Cut	Deep, 5–7 ft	Yes	Marginal
74+00 to 82+00	Fill	Thick, 6–8 ft	No	No
82+00 to 91+00	Cut	Deep, 4–6 ft	Yes	Low
91+00 to 105+00	Fill	Thick, 8–10 ft	No	No

Table 5. Listing of the possible critical areas with descriptions of issues. All the locations are cut areas.

Section	Previous or existing depressions	Description	Decision	Thaw critical ranking
8+00 to 17+00	Yes	Currently small depressions N. shoulder, nothing historically significant	Depression in shoulder only, suggest monitoring	Low to Marginal
33+00 to 35+00	No	No past or current depressions, shallow fill is noted	Suggest monitoring	Low
42+00 to 52+00	Yes	Currently many depressions along S. shoulder. Past depressions in the runway at 45+00 and at 50+00, also along south shoulder, but nothing now	Depression in shoulder only, suggest monitoring	Marginal
56+00 to 64+00	**Yes**	Currently numerous depressions across runway at 62+00 to 64+00, N. shoulder and outfield has very large depressions. Past depressions from 56+00 to 60+00 noted in the ACFEL 1955 report	The depressions on the S. shoulder contain ice, the depressions at the centerline and N. shoulder contain ice. Mitigation required.	**High**
64+00 to 67+00	Yes	Nothing current, past depressions (bird baths) were numerous from 65+00 to 67+00 on south side of runway	No depressions since the last repave, questionable fill thickness above 6 ft. Mitigation recommended.	Marginal
67+00 to 74+00	Yes	Currently one depression along centerline at 70+00, past depressions (bird baths) from 67+00 to 72+00 noted in ACFEL 1955	No ice in current depression, Mitigation recommended based on historical problems only	Marginal
82+00 to 91+00	Yes	Currently some depressions along N. shoulder. Nothing significant in the past	Suggest monitoring	Low

Table 4 suggests that seven areas should be scrutinized for thaw mitigation measures. Two areas, 33+00 to 35+00 and 82+00 to 91+00, were *low* on criticality, therefore monitoring only is suggested. Locations 8+00 to 17+00 and 42+00 to 52+00 were *marginal* on criticality and, lacking depressions either past or present, monitoring only is suggested. Locations 64+00 to 67+00 and 67+00 to 74+00 were *marginal* in criticality but with their proximity to the known runway depressions, mitigation is suggested. Finally, location 56+00 to 64+00 has depressions currently in the runway

and has had in the past; mitigation is required. The mitigation technique should be applied across the full width of the runway at the selected locations, and beyond the runway edge lighting where applicable.

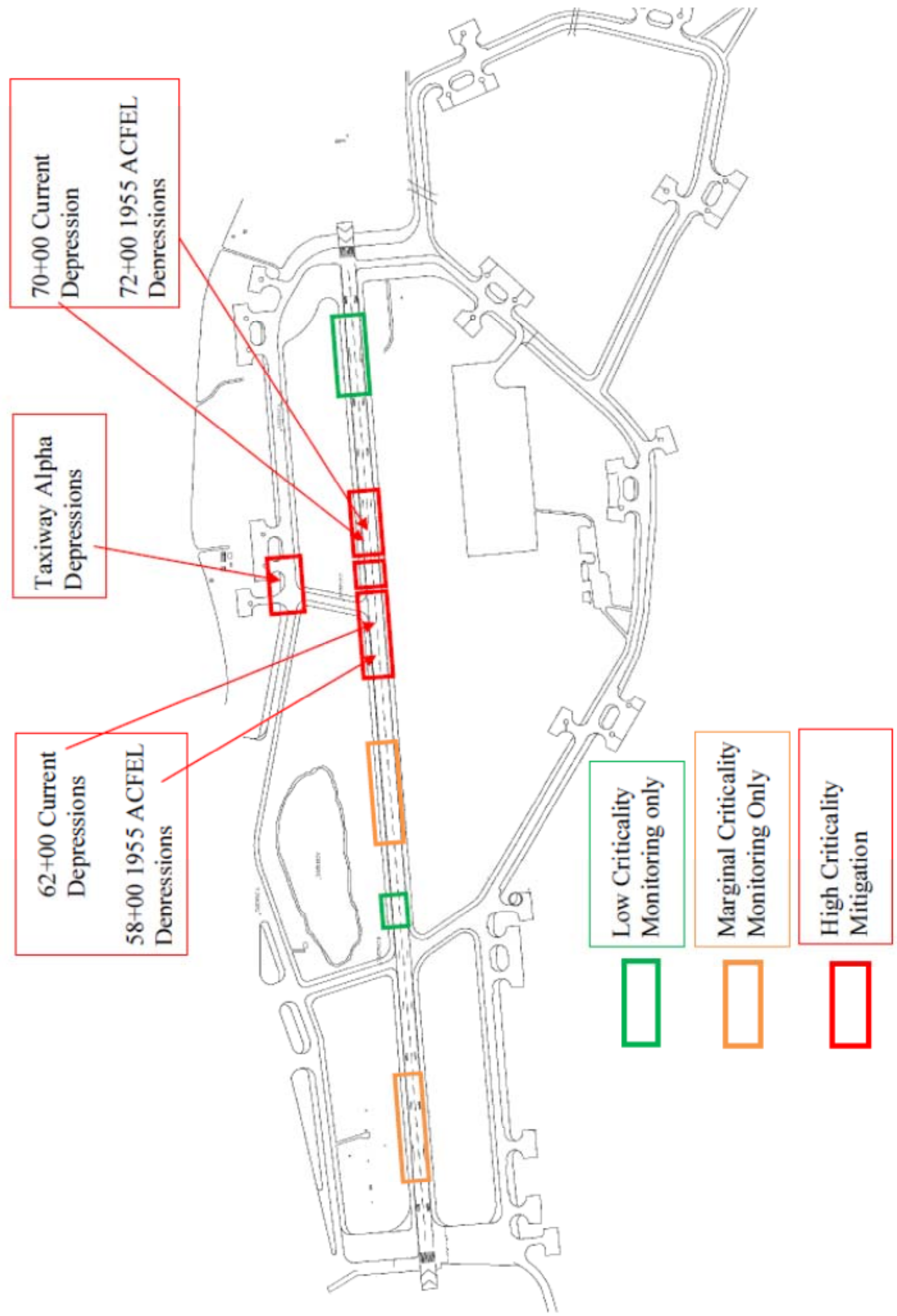

Figure 37. Plan view of the areas absolutely requiring and possibly requiring thaw mitigation.

Figure 37 is a plan view of the airfield and illustrates the areas in need of monitoring and mitigation. The total area requiring mitigating is about

18% of the runway surface, and areas requiring monitoring amount to 30% of the runway surface.

5.3 Thaw mitigation alternatives

To reiterate, the permafrost issue with the airfield, and most specifically the runway, is a combination of two factors. The first is massive wedge ice located in the native soils below the base course fill material. The second is the engineering design of 1951 using a minimal 6-ft fill thickness; it created a situation at some locations where this massive ice is close to the surface and, therefore, sensitive to thermal regime changes. Two alternatives exist to ensure that massive ice does not thaw: increase the thermal resistance to make certain that summer heat energy does not reach the massive ice, or remove the massive ice.

5.3.1 Insulation

The effectiveness of installing XPS rigid board insulation at depth was discussed in section 4.5. The field test and computer thermal modeling demonstrated that this alternative will perform as required. Extruded polystyrene (XPS) is a closed cell material and will not be adversely affected by water. High compressive and flexural strength insulation, up to 100 psi and above, is available specifically for direct bury in a structural embankment. It has been shown to perform well under these conditions. A minimum installed thickness of 4 in. is adequate for the current climate and soil conditions, and will perform as needed if the mean annual air temperature (MAAT) increases by 2 to 3°C. For an anticipated climate change of up to 6 to 8°C, 6 in. of EXP will be required. Figure 38 illustrates the concept and installation of the XPS.

The insulation would be installed at the specified locations for thaw mitigation and at the depth of 4 ft below the finished subgrade. This depth is optimal for ensuring that subsurface groundwater does not flow at a shallower depth than it is now. It also eliminates the possible issues with differential heaving between the insulated section and the adjacent uninsulated sections. Preferably, 4- × 8-ft sheets would be used and each sheet must firmly abut the adjoining sheet. The following layers should be staggered to overlap the previous layer's joints by at least 1/3. Care must be taken with the size of the earth-moving equipment used to minimize fill material lift thickness so as to not shift or damage the XPS. The 4-ft-deep excavation for installing the insulation should not encounter massive ice.

However, if this were to happen, the opportunity should be taken to over-excavate the massive ice to the fullest extent possible to ensure problem areas are mitigated.

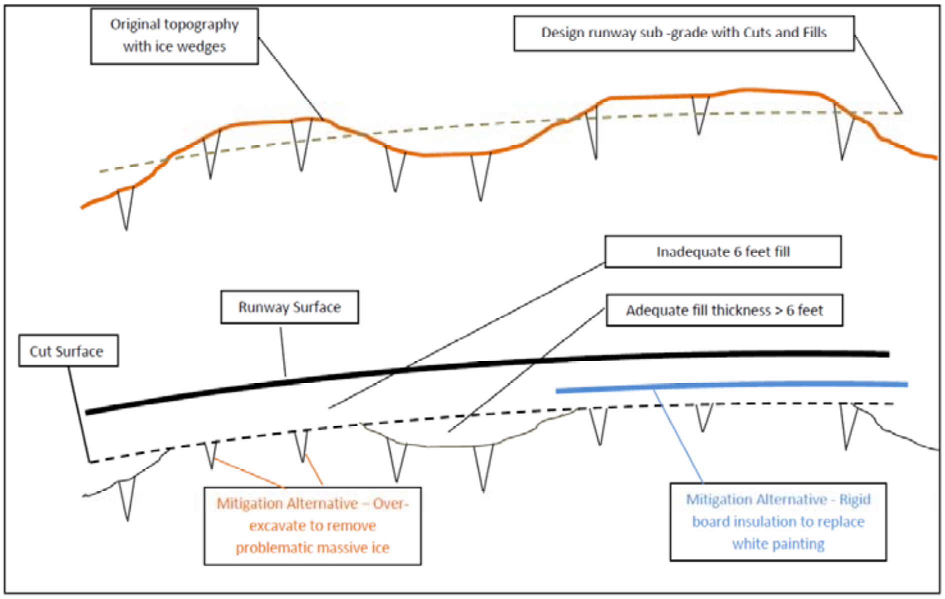

Figure 38. Thaw mitigation alternatives, over-excavation and insulation.

5.3.2 Over-excavation

Removal of the massive ice in known areas can nearly eliminate the possibility of thaw degradation. Excavation of the subgrade soils to the bottom depth of the thaw critical interval, or 9 ft, would allow for visible identification of massive ice that then can be surgically removed to beyond the depth of the thaw critical interval. If over-excavation is prescribed for a localized area with known massive ice, the entire subgrade to the full depth of the excavation should be removed and replaced with clean, compacted fill material. The only known locations for shallow ice in the active runway are 58+00 to 64+00 (Table 2). Figure 38 also illustrates the concept of over-excavation.

5.3.3 White asphalt

The creation of a white pavement suitable for cold regions performance, and with the ability to remain light colored throughout the design life, would effectively replace the white painting. To ensure a fully light colored bituminous pavement section with high albedo, both the aggregate and binder would need to be light colored. It is unknown if a high hardness, light colored aggregate exists in the immediate Thule area. Also it is un-

known if a light colored binder mix suitable for cold regions exists and would sustain the punishment of the Thule climate. A suitable pavement mix would require rigorous testing prior to the upcoming paving, and time is probably the limiting factor in that regard.

5.4 Halting the painting program

Four key items were discovered during the course of this investigation:

1. For the past three summers the center 100 ft of the runway has been nearly 100% unprotected by white paint during abnormally warm summers.
2. The investigation demonstrates that shallow ice-rich permafrost exists under only a very small percentage of the runway, and airfield in general. Therefore, white painting of the entire airfield is unnecessary.
3. It has been shown that the white paint has been inconsistent over the life of the painting program since 1958.
4. The effectiveness of the white paint is decreased dramatically if not maintained in a pristine white condition.

These items collectively suggest that the white painting is an overly conservative solution, with many drawbacks, and done at great expense. This information, and the possible delay of the repaving of the runway, creates an opportunity to better understand exactly how critical the issue is for permafrost and massive ice thawing at the airfield. Between now and the upcoming repaving cycle, the white painting program should be halted and the airfield should be heavily monitored.

This will serve two purposes. The first is to determine the exact thaw sensitivity of the airfield. Because ice was physically found at one location on the active runway (62+00) in current depressions, these depressions can be monitored discretely to watch for enlargement or deepening. Secondly, if depressions were to materialize at other locations, these sites would signal the areas needed for thaw mitigation during the repaving. If thaw settlement were to occur while white painting is halted, the depressions would be similar to those that exist now in the runway along the centerline at 62+00 (2 to 3 ft wide, 3 to 5 ft long, and 1.0 in. deep). They would develop very slowly over the summer season, and could be repaired with techniques already used by airfield maintenance personnel at Thule AB.

The thaw monitoring of the airfield can be done by personnel physically locating and measuring the known depressions. This baseline measuring should be made in the late spring or early summer of the first season of no painting. An additional survey of the runway for new depressions, and measuring the existing depressions again, should take place at the end of the summer. Additionally, there exists a stand-off technique to monitor vertical movement with satellite imagery. The technique requires that a digital terrain model (DTM) of the airfield be created (this was done in summer of 2011), and then successive synthetic aperture radar (SAR) images of the airfield be compared to the DTM and then processed for the vertical differential (Barboux and Gay 2009; Yuan 2011). This technique (InSAR) has been reported to capture movement within a tolerance of an inch, and images can be collected from a variety of platforms that are currently in orbit.

As mentioned previously, thaw settlement under pavement structures is generally not a catastrophic process, with a sudden loss of aircraft supporting strength. The scenario of an aircraft's weight causing collapse and a sudden fall into a deep thaw sink hole, or of a deep sink hole opening overnight or over a few days rendering the airfield useless until repair, generally does not occur in these situations. Numerous examples of thaw settlement are evident in regions with discontinuous permafrost. The settlement is noticed during and after the summer thaw, and with airfields and roadways, application of thin lifts of asphalt to fill depressions is the maintenance norm.

5.5 Drainage

Previous dedicated drainage studies for the airfield (Metcalf & Eddy 1958; Berg 1976) have been conducted. These studies suggest that flow originates from the slopes of South Mountain, with contributions from the area in the direction of DET-1, and then enters the southeast area of the airfield, flowing across the South Loop Taxiway into the runway area. Both studies suggest that the runway and taxiway embankments act as preferential flow paths, and when flow encounters an embankment it migrates longitudinally under its centerline. The studies suggest that a majority of the flow eventually discharges out of the north side of the runway embankment at approximately 80+00 to flow through the culvert under Taxiway Alpha east of Taxiway Charlie (Fig. 39).

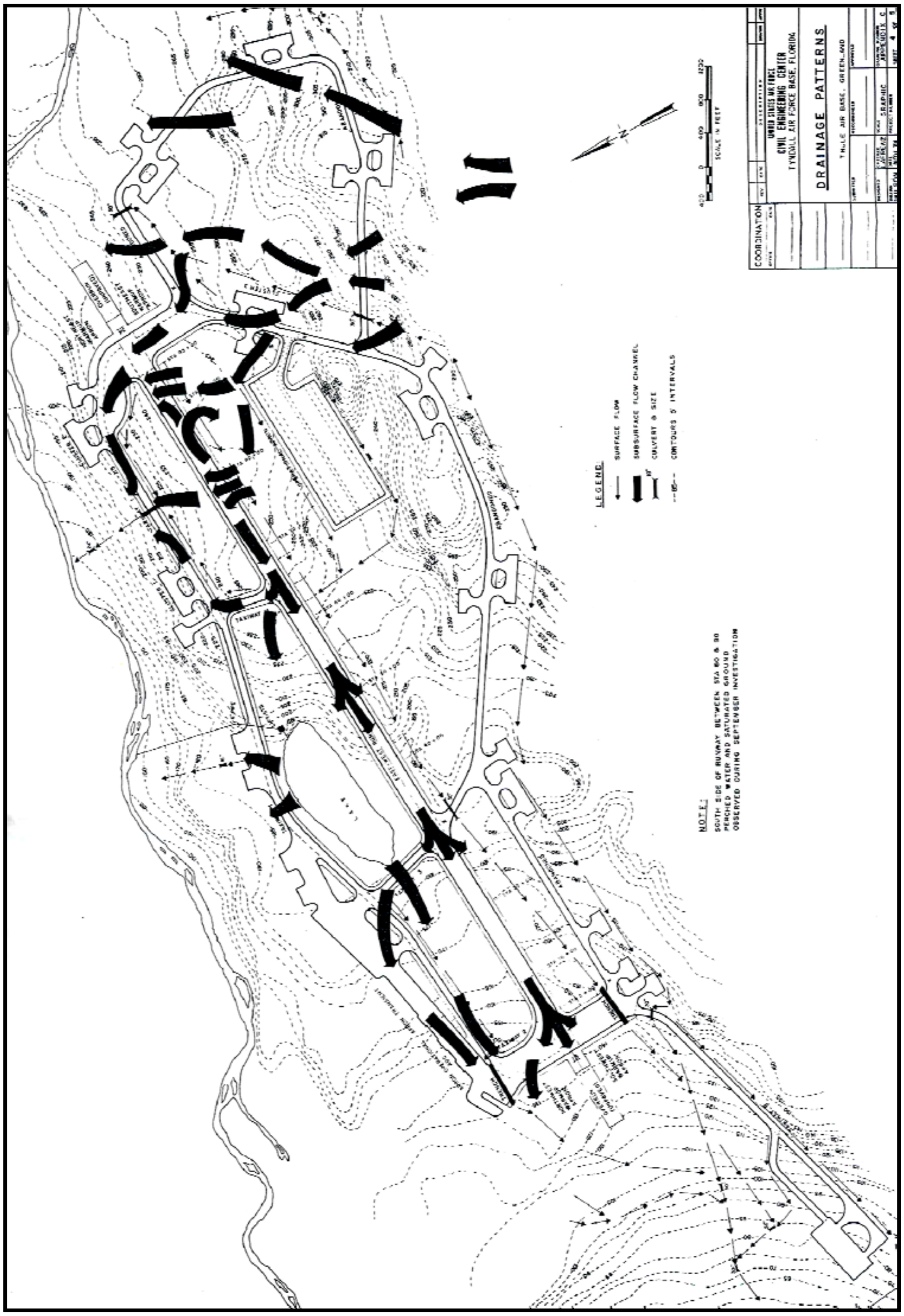

Figure 39. Surface water drainage paths and inferred subsurface drainage paths (AFCEC 1974).

Some flow continues to the west into Lake Eddy, under Taxiway Bravo and out under culverts to the west. In 1975, "bird baths" that had developed from 80+00 to 100+00 were suspected to be from groundwater weakened soils. Berg (1976) suggested white painting of this section of the runway; it

was done in 1977. Pavement overlay was done in 1977 and repaving in 1993 and this problem has not returned. The Metcalf & Eddy (1958) study suggests that a spring exists under station 85+00 of the runway with no explanation. A spring migrating through cold, continuous permafrost is very unlikely.

5.5.1 Subsurface water

Groundwater migration mostly depends on the depth of the seasonal thaw of the active layer. When the snow and ice begins to thaw in the spring, this meltwater can only flow on the surface because the active layer is completely frozen from the winter. Information from operators of the airfield describe water running over the South Loop Taxiway near the intersection with the 26 end of the runway, and at the intersection of the South Loop Taxiway and Taxiway Alpha near the 08 end of the runway, and this occurs in the very early spring season.

Over the summer, as the thaw progresses down through the active layer, the thaw depth allows for subsurface flow, so there is a noticeable decrease in surface flow as the season progresses. This coincides with the diminishing supply of snow and ice for meltwater. At the end of the summer season, the active layer is completely thawed and water can migrate at any depth in the active layer, but will primarily flow along the top of the permafrost. The decreased depth of seasonal thaw, attributable to white pavement, forces the water to flow at a shallower depth than if the pavement were naturally colored.

A finite element computer analysis was performed to see if subsurface water could possibly flow down the center of the airfield embankments. An idealized embankment was constructed with a 6-ft gravel fill section overlying a 4-ft active layer, these both in turn overlying an 18-ft thick permanently frozen till. Figure 40 shows that the swales at the transition from the embankment to the native soil grade would be the lowest elevation along the cross section. The top of the permafrost in the embankment will be at a higher elevation than the top of the permafrost in the native material adjacent to it, creating a damming effect that resists groundwater movement from one side of the embankment to the other. Therefore, a more realistic scenario than that suggested by the previous drainage reports is that lateral flow of groundwater under the runways and taxiways is altered or blocked, diverting the groundwater in complicated ways.

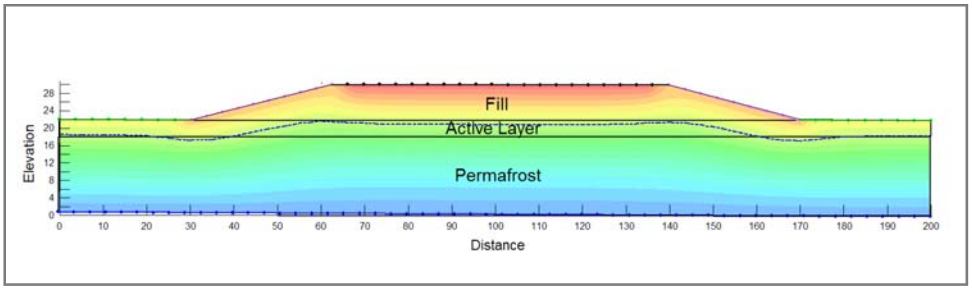

Figure 40. Numerical analysis of thaw depth in a 6-ft fill embankment constructed on natural grade. The colors represent end-of-analysis temperatures, with blue the coldest, and red the warmest. The depth of thaw after one season is represented by the blue dotted line. The raised permafrost table into the fill produces swales at the embankment toe and a damming effect that would prevent lateral flow of groundwater from shoulder to shoulder.

The original topography of the airfield has significant elevation changes where the runway drops 84 ft from centerline of station 100+00 to centerline of station 00+00 (east to west). Generally, the runway is a topographic high point of the airfield, with all taxiways ascending to meet the runway. The exception is the extreme southern extent of South Loop Taxiway, which climbs a lower reach of South Mountain and overlooks the SAC ramp. This taxiway then descends to the southeast section of the airfield to eventually meet with the 26 end of the runway at 100+00. Berg (1976) recommended painting the remainder of the runway from 80+00 to 100+00 in an effort to establish a "damming effect" and prevent water from weakening the subbase soils. Because this section was constructed with a large amount of fill mostly exceeding 6 ft deep, the permafrost table in this section would provide a damming effect regardless of the color of the pavement. White painting this section did not relieve the "bird bath" problem; more likely, the 1992 repaving with subbase restructuring achieved the desired results.

5.5.2 Seeps

The information gathered during this study suggests groundwater pathways have been established within the embankment system and water migrates in these locations year after year. This is demonstrated by the cluster of seeps that flow through the runway shoulder and lighting in the area of 38+00 on the north side of the runway, and a large seep located at 05+00 off the south shoulder.

During peak water flow in the late spring and early summer, and after substantial rain events, water will seep from the north shoulder of the runway

adjacent to Lake Eddy; the soils immediately north of the paved shoulder will remain wet to saturated, and the electrical vaults will be filled with water (Fig. 41). Small seeps exist further north of the shoulder and just above the level of Lake Eddy and they drain into the lake. The pavements in this north shoulder area appear to be distressed by freeze–thaw cycling and staining is visible, suggesting prolonged water flow. Anecdotally, Air Base personnel report that in some cases the water will seep from the pavement of the runway, but only briefly, and there appear to be no lasting effects on the runway pavement in this area. A large seep is located in the outfield area to the south of the runway at approximately 10+00. This seep has existed for many years and can be seen on historical aerial photos. This specific location was a small lake prior to the construction of the airfield. This seep was excavated in 2008 and rock was encountered at approximately 2.5 to 3 ft below the surface. A large amount of water began to flow into the pit at an estimated 20 to 30 gal./minute as the excavator removed soil. The ultimate depth of the pit was only 4 ft owing to the difficulty of excavation in very large rock. The pit rapidly filled with water; however, it appeared that as the water reached the top of the pit, the flow rate diminished and returned to the pre-excavation flow rate of less than 5 to 7 gal./minute.

Figure 41. North shoulder of runway at 38+00. Seepage water is flowing from the electric vaults, and the visible splotchy asphalt of the shoulder is coincident with this area suggesting fatigue due to weakening of the base course or freeze–thaw problems. Water flows from the locations of the runway lighting early in the thawing season, slowly diminishing over the summer.

The location of these seeps at 38+00 are higher than any natural surface laterally adjacent to the runway; however, longitudinally it is 41.7 ft lower

than the highest point of the runway at centerline of 100+00. The elevation change from centerline of 100+00 to the seepage off the pavement at 05+00 is 85.8 ft. Seeps were also noticed on the very lower reaches of the 08 end overrun embankment along the south side. Photo comparison from September 2006 shows that all the aforementioned seeps existed at that time, and have been noticed in historical photos as well. Based on these elevation differences, water suspected of entering the embankment system at the 26 end of the runway could have sufficient head to push flow through this high permeability fill material over 9000 ft down-runway.

5.5.3 Depressions and groundwater

The depressions on the runway near 60+00 appear to have a preferential orientation from north-northwest to south-southeast. As noted earlier, it is probable that the majority of the groundwater flow enters the airfield from the southeast flowing to the northwest, and the depressions generally are in line with this orientation. This could be interpreted as thermal erosion from groundwater flow, where the water has found pathways along the top of the permafrost, possibly along wedge ice. However, the excavations of pits directly north of these depressions in the infield encountered ice at 5.5 ft, with very little or no groundwater. Also, boreholes drilled at the depression in the active runway and along the north and south shoulder did not show excessive water. The lack of groundwater does not dismiss this hypothesis, especially because the pits were dug so late in the summer season. The Metcalf & Eddy (1958) report shows a significant pond of water between the runway and the SAC Ramp, which does not exist today, most probably because of extensive ditching in this area to drain this pond to the west. Groundwater communication between the runway and the SAC ramp would be nearly impossible given the relief of the ditch in-between. This ditch was not shown on early plan maps, and the date of its construction is not known.

When the validated topographic information for the terrain model was compared to the electrical earth resistivity surveys (CCER), it can be seen that two highly conductive regions exist approximately in the middle of the runway embankment (Fig. 42) at approximately 52+00 and 62+00. These locations correspond to the topographic lows at 52+00 and 62+00. The location at 52+00 is a drainage course that existed prior to construction and would have originated on the south side of the runway at approximately the south shoulder area, extending to the northwest becoming the primary, and possibly only, surface water tributary into Lake Eddy. Sub-

surface flow might now exist at this location under the runway to Lake Eddy. However, owing to the extreme climate at Thule, it is rather improbable this flow is any deeper than the bottom of the seasonal frost. Also, subsurface flow would pipe material from the embankment, most probably causing larger scale settlement at the surface, and this is not seen. The location at 63+00 corresponds to a relative low region within the very large cut made from 56+00 to 74+00. The GPR profiles image very sharply dipping reflectors in this area, and this also corresponds to the location of the depression at 62+00 to 63+00. (Fig. 43) The bottom of the highly conductive region at 63+00 is 16 ft deep, and this corresponds with the depth of the reflectors in the GPR image at 16 ft.

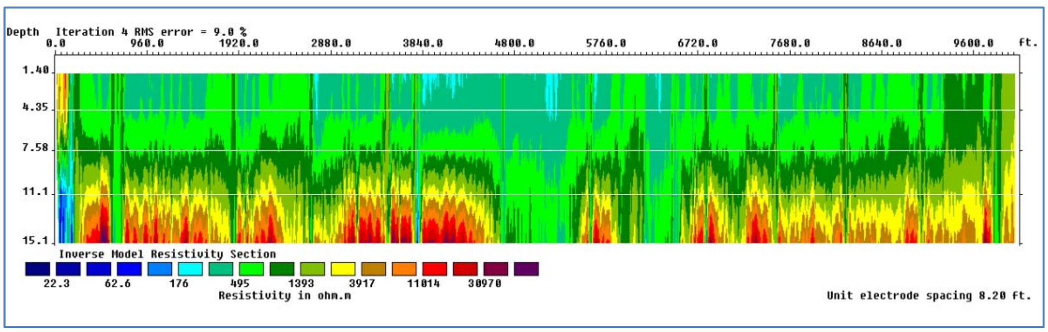

Figure 42. Runway resistivity cross-section from 00+00 to 100+00. The locations of the pre-construction surface drainage feature at ~52+00, and the location of the existing depressions at 62+00 are visible in blue with the lower resistivity (high conductivity). The undulating frozen ground boundary is also clearly defined by the yellow and red shading. (Depth scale is exaggerated in this figure.)

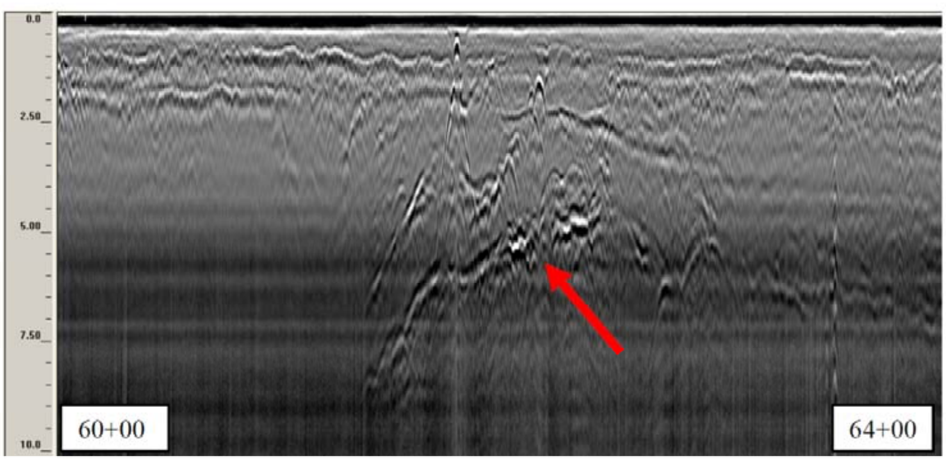

Figure 43. GPR image showing from 60+00 to 64+00. Isolated reflectors are shown at ~63+00 at a depth of ~16 ft. The bright black-white-black reflectors (red arrow) are typical of the sedimentary bedrock reflections.

5.5.4 Diurnal drainage changes

In the earlier part of the summer snowmelt season, noticeable changes in surface and subsurface water flow are possible from changes in air and surface temperature caused by movement of the sun and cloud cover. Although there would be some time lag, it would be possible to notice reduced flow in the culverts in the morning vs. afternoon. However, because of the heat capacity and thermal conductivity of the soil and associated moisture, hourly changes to the thaw depth or freeze depth do not occur. Neither do significant diurnal changes in thaw or freeze depth of either the active layer or permafrost.

5.6 Drainage summary

If water does migrate to the 26 end (east) of the runway embankment from the southeast, as suggested by others, and then westward from 100+00 toward 63+00 or further toward 52+00, this would most probably happen under the shoulders and not directly under the centerline. The seep locations in the shoulders help to confirm this hypothesis. The water could then preferentially flow across the runway embankment and into the active layer on the north side of the runway, and then either to Lake Eddy or elsewhere. This would create annual pathways for water flow longitudinally and laterally across the runway embankment, and would explain the low resistivity anomalies (blue color) identified in Figure 42. Some of this flow must continue westward in the embankment on the top of the permafrost table or through less flow resistive material above the permafrost. It then exits at the 38+00 seeps or further at the seeps at 05+00 on the south side.

6 Recommendations

At the start of this investigation in 2008, the anticipated date for the repaving was FY12. This effectively provided enough time to assess the issues and make recommendations for thaw mitigation to be incorporated into the repaving design. Because the repaving has been delayed, it allows an opportunity to make airfield operational changes that could provide substantial information for the final repaving design.

6.1 Insulation

Based on the modeling and field testing of the insulation, the primary alternative is to install 4 in. of XPS insulation at the 4-ft depth at all locations requiring thaw mitigation. Table 6 groups the mitigation areas that were listed in Table 5 into three risk categories that can be used as a guide to help determine the level of risk associated with the level of mitigation deemed appropriate. Below is a description of the risk levels in Table 5.

1. *High*—The primary location for mitigation is listed as *High* in Table 5 and is from 56+00 to 64+00. This is based on the current thaw depressions in the area, along with the results of the drilling, and should be mitigated in all circumstances. However, if this was to be the only area mitigated, as shown in Table 5 under *High* risk, this area should be expanded from 56+00 to 74+00 to mitigate all the area that has previously been affected, is currently affected, and in which the field results indicate ice within the thaw critical interval.
2. *Marginal*—The next group of areas incorporates the area listed above in the *High* risk alternative to those areas listed as *Marginal* in Table 5. These additional areas do not exhibit current or recent thaw activity, but the historical thaw activity along with the field investigation suggests possible ice-rich material within shallow reach of the bottom of the current thaw depth.
3. *Low*—The final group of areas incorporates those places listed in the *Marginal* risk alternative above to those listed as *Low* in Table 5 and is the most conservative approach, but most costly. These are all the areas where the investigation suggests ice-rich native soils are within the thaw-critical interval. Therefore, this includes the areas with past degradation, and those with current degradation.

Table 6. Areas recommended for thaw mitigation categorized by level of risk. All areas are assumed full runway width for mitigation.

Risk	Locations	Notes	% Total runway
High	56+00 to 74+00	Area to be mitigated includes historical and current thaw degradation, and confirmed ice. Shoulders were not included into the width of the total area computation. It should be noted the shoulders are ice rich at 59+00 S. Shoulder, and 62+00 N. Shoulder.	18%
Marginal	8+00 to 17+00, 42+00 to 52+00, 56+00 to 64+00, 64+00 to 67+00, 67+00 to 74+00	All areas to be mitigated that historically have had thaw degradation, and currently have thaw degradation.	37%
Low	8+00 to 17+00, 33+00 to 35+00, 42+00 to 52+00, 56+00 to 64+00, 64+00 to 67+00, 67+00 to 74+00, 82+00 to 91+00	All areas to be mitigated based on the possibility of ice-rich soils within the thaw critical interval. Includes if the area has a history of thaw degradation, current depressions, or existence of ice.	48%

6.2 Cease white painting

Because the lack of white painting has effectively been tested for the last 3 years under the warmest of summer conditions, it is recommended that this test be extended by ceasing the white painting program as soon as possible. This will demonstrate the degree of thaw sensitivity of the airfield, beyond that which has occurred to date with the current paint loss along the runway keel, and the historical non-pristine nature of the painting in general. During this period, the areas that have been identified as potentially having thaw mitigation issues would be given time for degradation to initiate, indicating absolutely if mitigation is required during the next repaving. If re-leveling is required before the repaving, maintenance procedures are available at Thule to address those areas. Diligent monitoring of the airfield for any settlement will ensure that no adverse impact is created from this procedure. Observations by the current author of active thaw settlement and thaw affected linear structures (airfields and roadways) in Alaska and Canada support this recommendation. The settlement will not be catastrophic, will not decrease the reliability and operation of the airfield, and can be halted at any time using white painting or the techniques described above. This would allow for the refinement of Table

6 by defining the risk categories more discretely, providing refinement of the repaving design. The InSAR technique to monitor subsidence should be employed as a check to physical measurements.

Another benefit of ceasing the white painting will be to monitor the effect of the deepening thawed layer on the subsurface water movement, and the seepage around the airfield, especially at the N. Shoulder at 38+00.

7 Conclusions

This investigation has shown that ice-rich native soils are not located at the same depth at all locations under the airfield, where greater than 50% of the runway alone is located over significant fill depths that do not need thaw mitigation. The initial design put the shallow, ice-rich native soils at these few select locations 6 ft under fill material; however, 6 ft is insufficient to currently prevent thaw without mitigation. The exception to this thickness may be where the box section was installed from 61+00 to 75+00 in 1952 to mitigate shallow fill thickness over a change in slope design. This area coincides with the current depressions found at the airfield now at 62+00 and 70+00, and this section will require mitigation in all circumstances.

The white painting reduces thaw depth, helping to prevent thawing of near-surface ice-rich native soils. Under pristine, bright white conditions, thaw depth can be held to approximately 4 ft. However, slight fading, or wear of the paint where the brightness is reduced only minimally, dramatically lowers albedo and increases thaw depth by 1 ft or more. Although the evidence is spotty, it appears the airfield has not had pristine white conditions everywhere since the inception of the painting program. This means that the overall average thaw depth through the years has been much greater, possibly approaching that of the design 6-ft fill thickness.

Unfortunate consequences of the painting program are the reduction in aircraft braking ability, and increase in operation costs. The upcoming repaving project will be an excellent opportunity to eliminate costly painting and incorporate alternative methods of thaw mitigation at identified locations with insufficient fill depths. Of the two thaw mitigation alternatives presented here, subgrade insulation installation offers the greatest design flexibility and cost assuredness, in comparison to over-excavation of the massive ice.

Three mitigation scenarios, with varying amounts of the total extent of insulation installed, were presented to allow for flexibility in the repaving design. Further, ceasing the white painting program is recommended. A significant level of information would be gained by this procedure, and would better ensure that conservative engineering does not mitigate areas

unnecessarily, driving up the repaving costs. Diligent monitoring of the airfield for any settlement will ensure that no adverse impact is created by this procedure.

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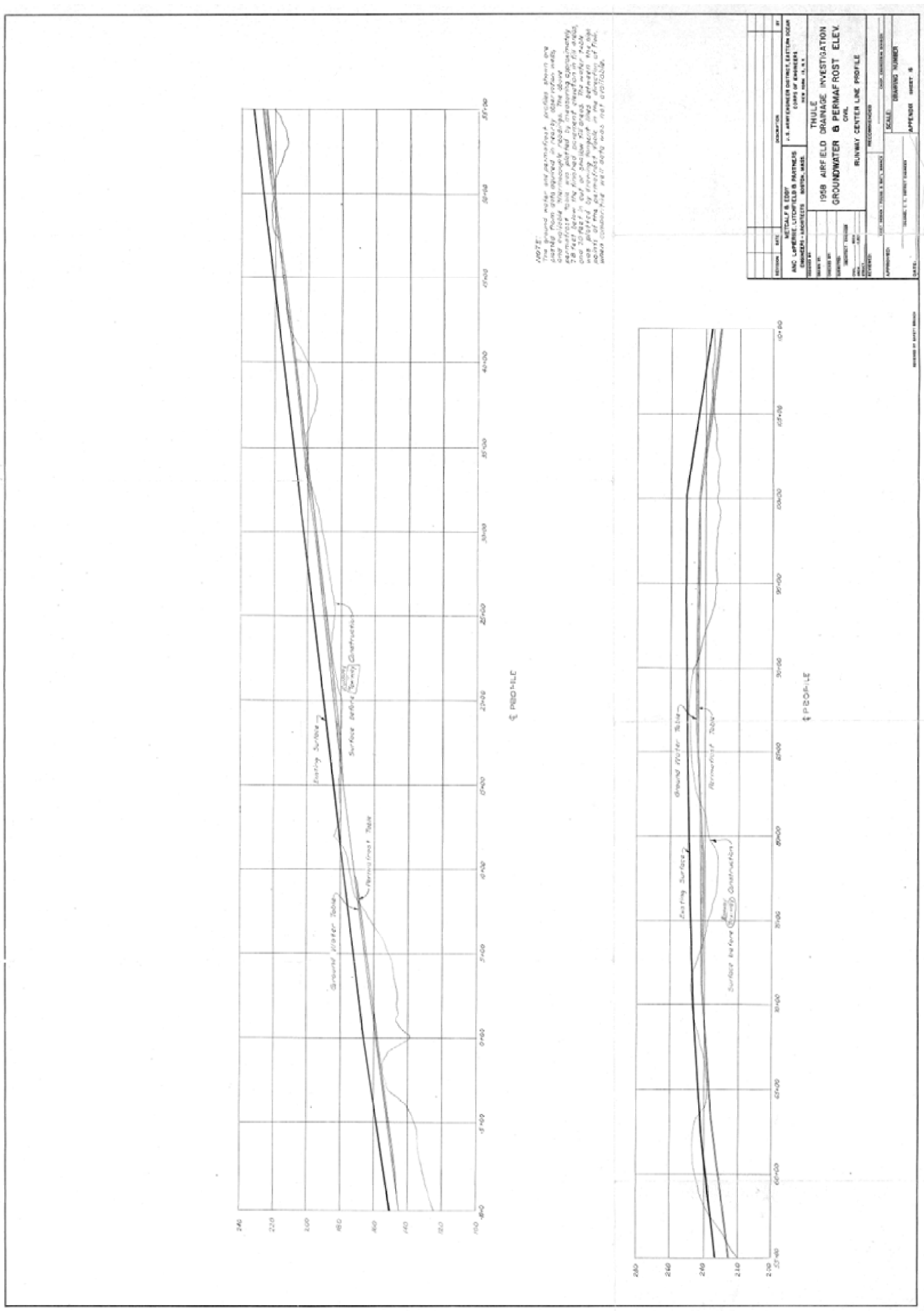
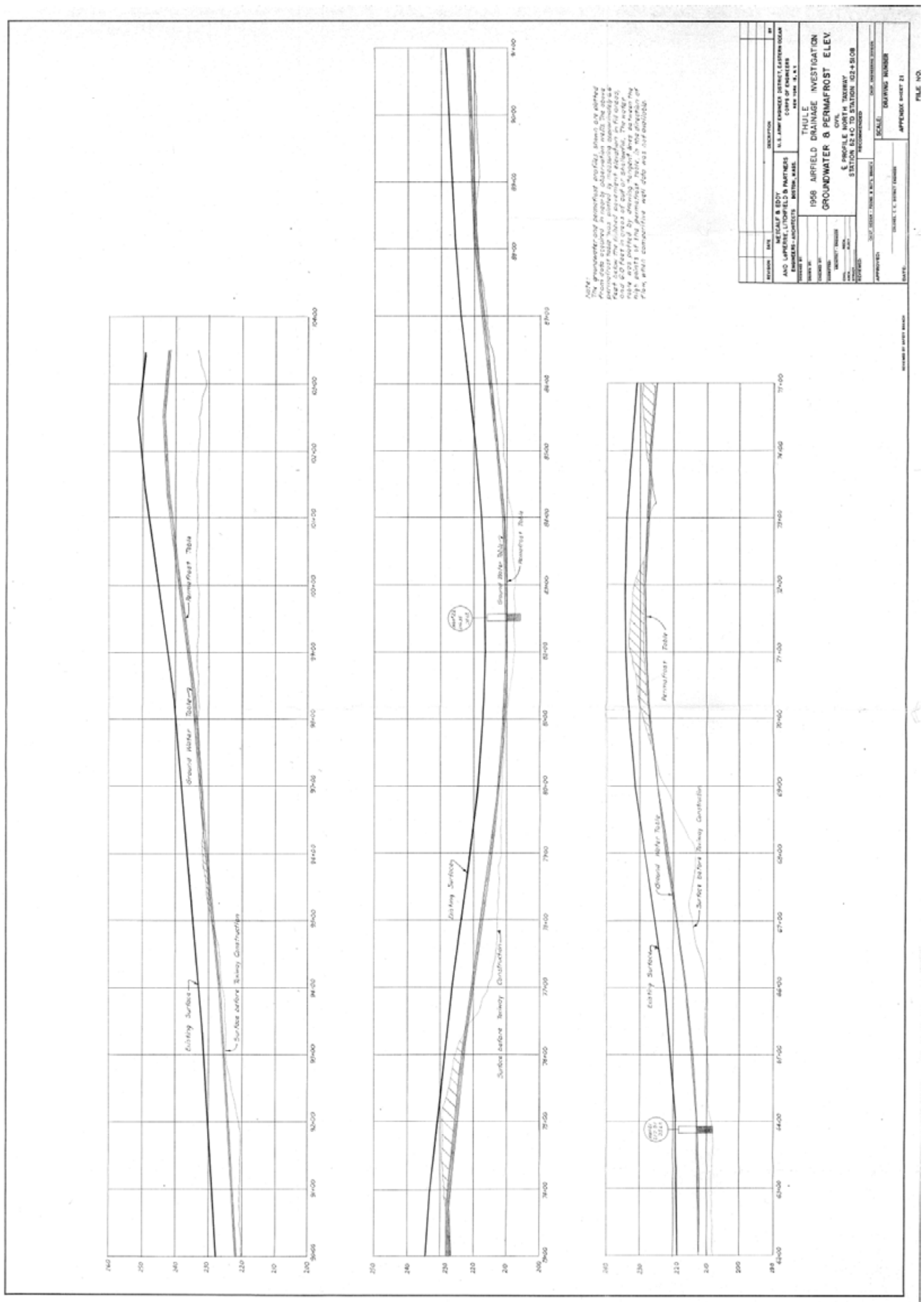
Appendix A: As-Built Plans, Metcalf & Eddy (1958)

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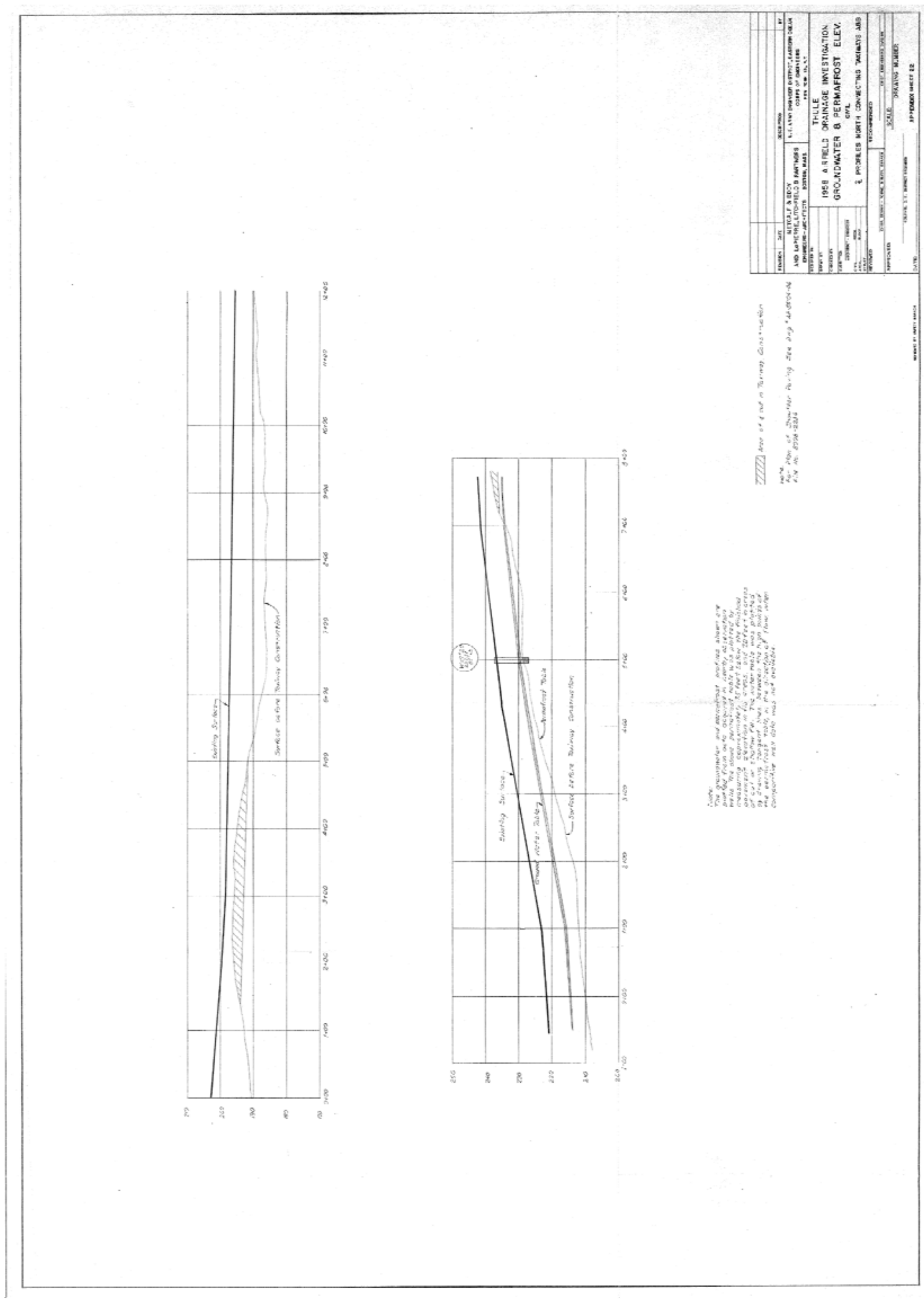
AND LAPIERRE, LITCHFIELD & PARTNERS
ENGINEERS - ARCHITECTS BOSTON, MASS.
U.S. ARMY ENGINEER DISTRICT, EASTERN OCEAN
CORPS OF ENGINEERS
THULE
1956 AIRFIELD DRAINAGE INVESTIGATION
GROUNDWATER & PERMAFROST ELEV.
CIVIL
℄ PROFILE NORTH TAXIWAY
STATION 52+C TO STATION 102+51.08
DRAWING NUMBER
FILE NO.
Existing Surface
Surface before Taxiway Construction
Ground Water Table
Permafrost Table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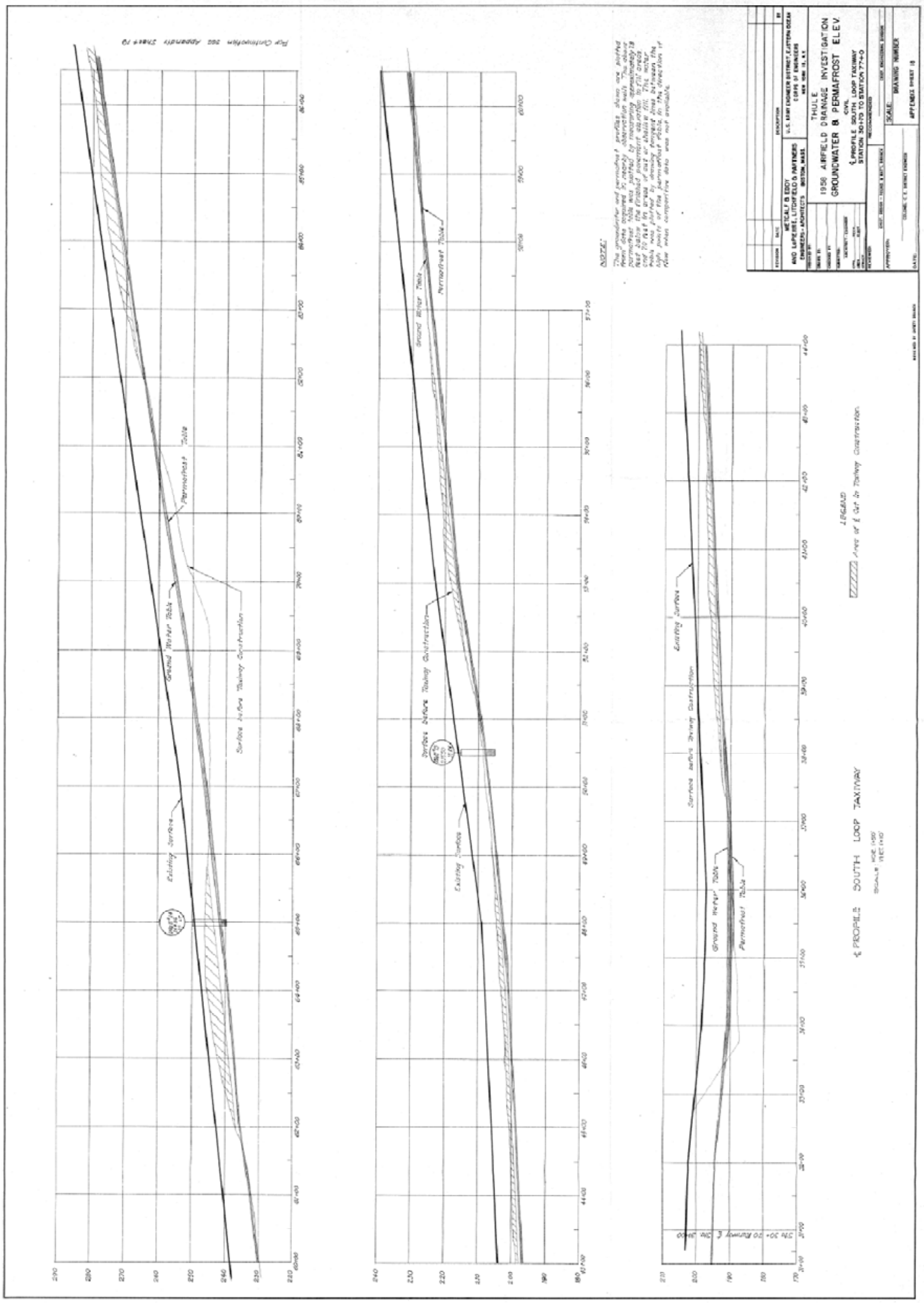
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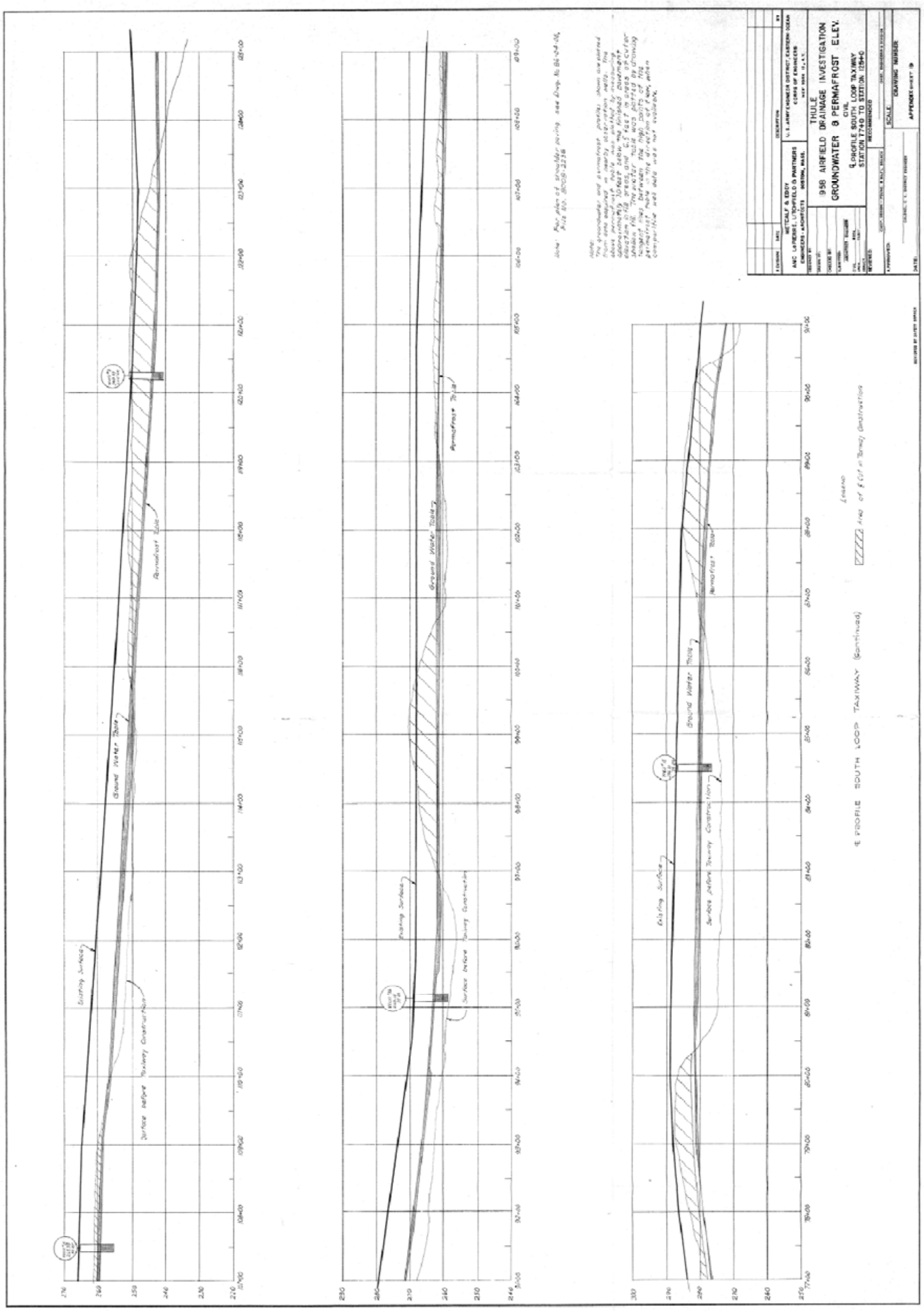
GROUNDWATER & PERMAFROST ELEV.
LEGEND
℄ PROFILE SOUTH LOOP TAXIWAY


THULE
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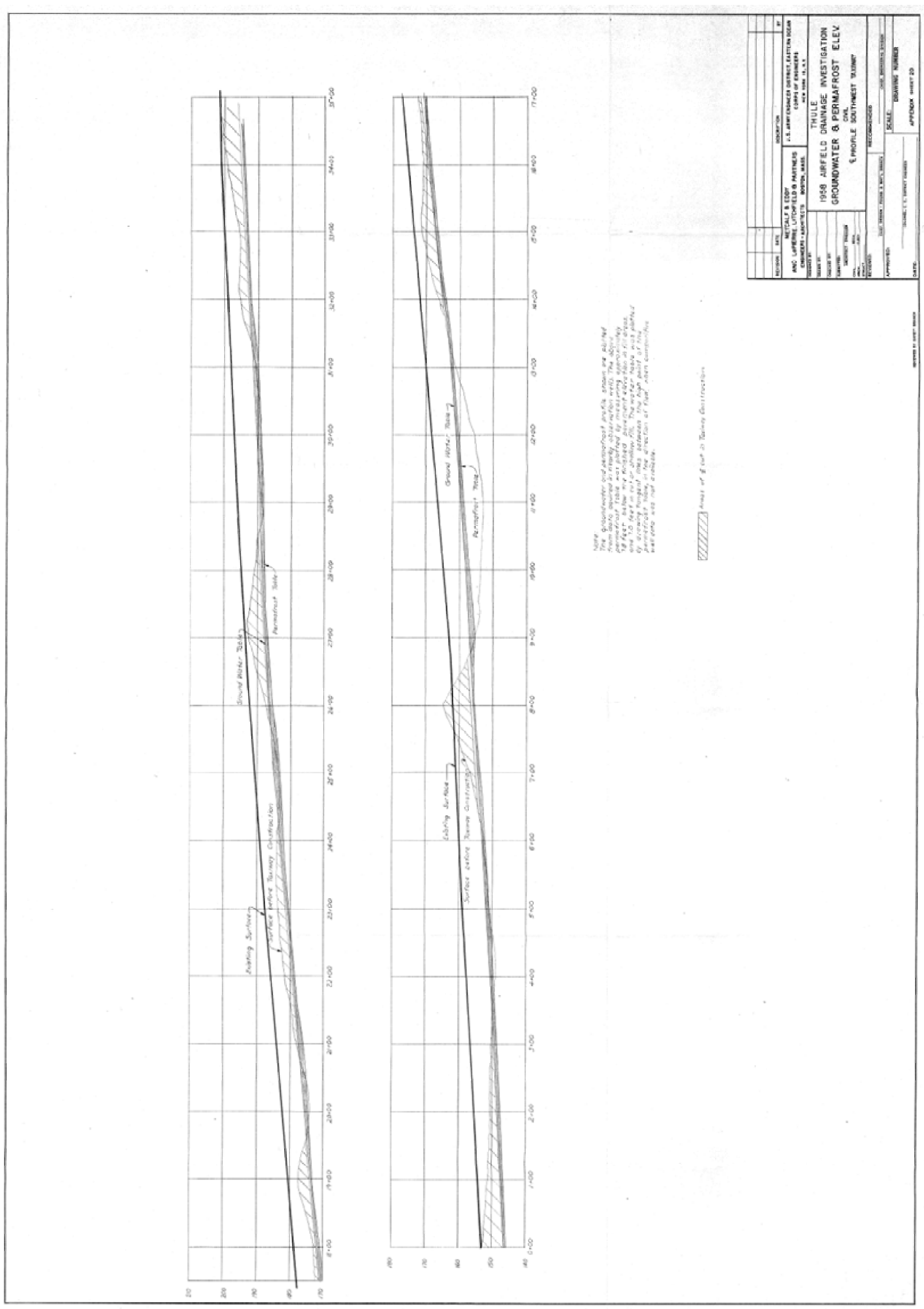
METCALF & EDDY
Existing Surface
Ground Water Table
Permafrost Table
Surface before Taxiway Construction
Legend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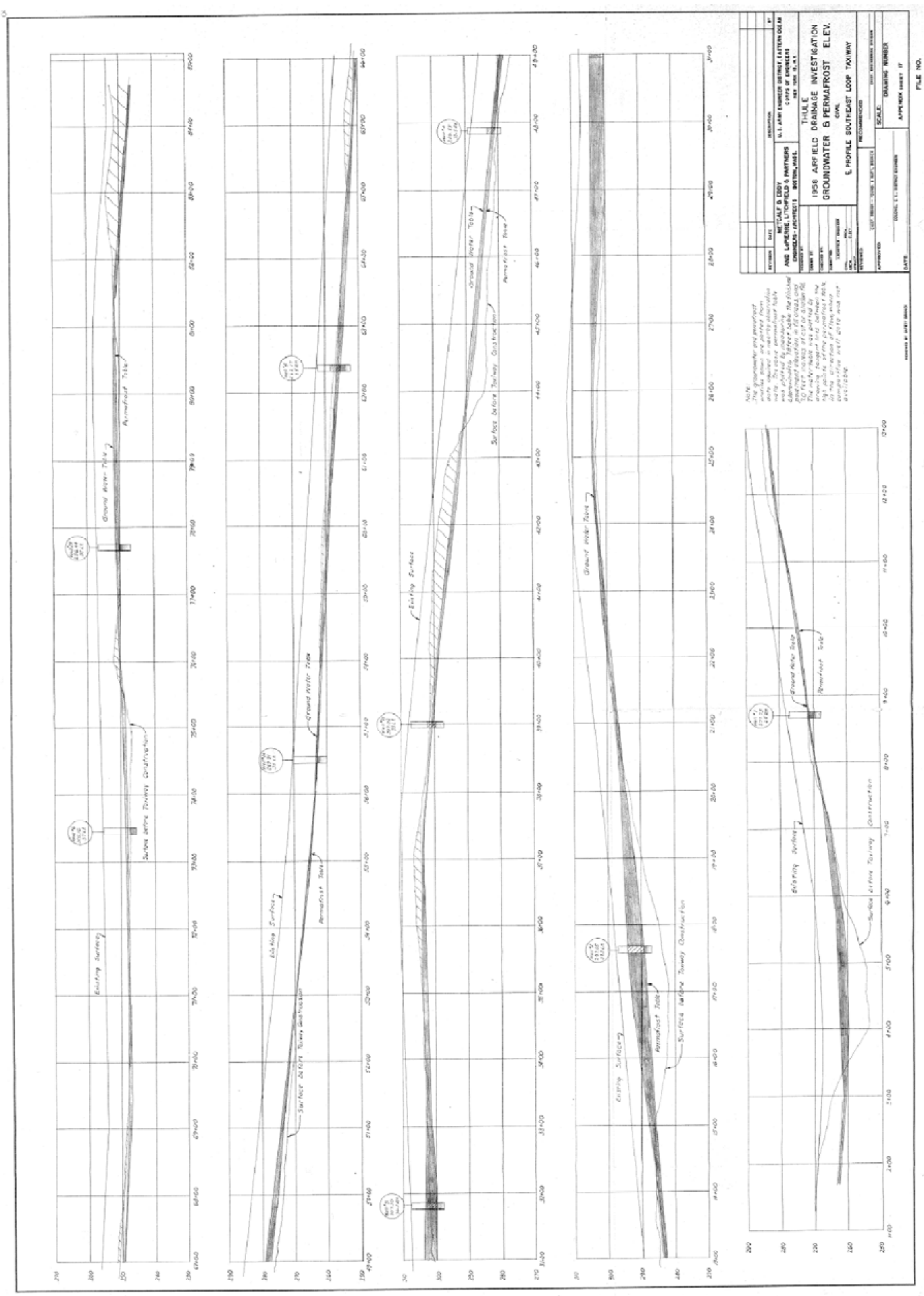
CORPS OF ENGINEERS
THULE
1958 AIRFIELD DRAINAGE INVESTIGATION
GROUNDWATER & PERMAFROST ELEV.
CIVIL
℄ PROFILE SOUTHWEST TAXIWAY
SCALE:
DRAWING NUMBER
APPENDIX SHEET 20
Ground Water Table
Permafrost Table
Existing Surface
Surface before Taxiway Construction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FILE NO.

Appendix B: Boring Logs

BH #	Distance	Description	AC thickness (ft.)	Thickness of Saturation Zone (ft.)	Frozen depth (ft.)	Ice depth (ft.)	Ice thick (ft..)	Refusal material	Bottom of Hole (ft.)	Remarks
1	59+00	Depression North Outfield			5.0	6.0	2	Clay/Rock	9.0	
2	59+00	Adjacent to BH 1			5.0			Clay/Rock	7.0	
3	59+00	Adjacent to BH 1			5.0			Clay/Rock	8.0	
4	59+00	Adjacent to BH 1			5.0	6.0	1	Clay/Rock	10.0	
5	62+00	Runway Depression 10 N. of CL	0.5		5.0	7.0	2	Clay/Rock	8.0	
6	62+00	Depression 30 ft East of #5	0.5		5.0	7.0	0.5	Clay/Rock	8.0	
7	62+00	Slight Depression 25 ft West of #6	0.5		6.0	7.0	0.5	Clay/Rock	8.0	
8	51+50	Slight Depression 10 ft S. of CL	0.5		6.0			Fill	8.0	
9	00+00	60 ft West of Threshold	0.2	0.5	6.0			Fill	10.0	
10	07+50	25 ft N. of lights in paved shoulder	0.2	0.5	6.0			Fill	10.0	
11	13+50	25 ft N. of lights in paved shoulder	0.2	Wet	5.0			Fill	7.5	Distressed Pavement
12	17+75	10 ft N. of lights in paved shoulder	0.2		5.0			Fill	7.0	Distressed Pavement
13	19+75	15 ft N. of lights in paved shoulder	0.2		6.0			Fill	8.0	Some segregated ice
14	22+50	10 ft N. of lights in paved shoulder	0.2					Rock	5.0	Drilled 4 holes all refused at 5 to 5.5
15	23+50	12 ft N. of lights in paved shoulder	0.2		5.5			Fill	7.0	
16-A	31+50	10 ft N. of lights in paved shoulder	0.2	1.0	5.5			Rock	5.5	Drilled second hole refusal at 6 ft
16-B	34+00	20 ft N. of lights in paved shoulder	0.2						5.0	
17	34+00	North of paved shoulder 45 ft		Wet	5.0			Fill	10.0	Drilled in outfield area
20	40+00	20 ft N. of lights in paved shoulder	0.2		5.0	6.0	1.0	?	7.0	Very thick fill section

BH #	Distance	Description	AC thickness (ft.)	Thickness of Saturation Zone (ft.)	Frozen depth (ft.)	Ice depth (ft.)	Ice thick (ft..)	Refusal material	Bottom of Hole (ft.)	Remarks
21	45+00	10 ft N. of lights in paved shoulder	0.2		5.5			?	5.5	
22	46+00	20 ft S. of lights in paved shoulder	0.2		5.0			Fill	6.5	Big depression. Much pore ice
23	46+00	20 ft S. of lights in paved shoulder	0.2					Rock?	5.0	Big depression adjacent to BH #22
24	49+25	S. shoulder cluster of depressions	0.2		5.0			Rock?	5.0	Begin drilling cluster of depressions
25	49+40	12 ft east of #24	0.5	0.75	5.0			Rock?	6.0	
26	49+50	10 ft east of #25	0.75	0.75	5.5			Rock?	6.5	
27	49+75	25 ft east of #26	0.2	0.5	6.0			Rock?	6.0	
28	49+95	20 ft east of #27	0.2					Rock?	5.5	
29	50+00	S. shoulder	0.2					Rock?	5.5	
30	50+15	S. shoulder	0.2	0.5				Fill?	7.0	
31	50+75	33 ft S. of runway lights	0.2	Wet	5.0			Rock?	7.5	
32	58+60	20 ft S. of lights in paved shoulder	1.0		5.0			Rock?	6.0	Big Depression
33	59+00	27 ft east of #32	2.0		5.0			Rock?	5.0	
34	59+10	10 ft east of #33	1.5	0.5	5.0	5.0	2.0	Rock	7.0	
35	59+20	10 ft eastof #34	1.0	0.75	5.5	6.0	0.3	Rock?	6.5	
36	59+50	30 ft east of #35	0.5		5.0	5.5	1.5	Rock	7.0	
37	59+85	45 ft east of #36	0.3		5.0	5.5	0.5	Rock	7.0	
38	59+95	10 ft east of #37	0.2		5.0	5.0	1.0	Rock	6.0	
39	59+95	6 ft north of #38	0.3		5.0	5.0	1.0	Rock	6.0	
40	60+10	20 ft east of #39	0.8	0.6	5.0	6.0	2.0	Rock	8.0	
41	60+40	30 ft east of #40	0.8		5.0	6.0	0.5	Rock	6.5	Last hole in long line of depression
42	61+70	18 ft S. of lights in paved shoulder	0.3		5.0			Rock?	7.5	
43	50+00	24 ft N. of lights in paved shoulder	0.2	1.0	5.0			Rock?	8.0	Pore ice
44	30+20	6 ft N. of runway CL	0.4		5.0			Rock	10.0	Adjacent to depression
45	53+00	50 ft N. of lights in paved shoulder	0.2		5.0			Clay/Rock	7.5	Pore ice
46	58+35	10 ft S. of pavement edge in pavement	0.2		5.0				7.5	Adjacent to big depression in outfield
47	58+35	20 ft N. of #46 in			5.0	5.5	3.5		9.5	Depression in

BH #	Distance	Description	AC thickness (ft.)	Thickness of Saturation Zone (ft.)	Frozen depth (ft.)	Ice depth (ft.)	Ice thick (ft..)	Refusal material	Bottom of Hole (ft.)	Remarks
		outfield								outfield next to pavement
48	60+30	27 ft N. of lights in paved shoulder	0.2		5.0	5	3.5		8.5	Depression
49	66+75	5 ft N. of runway CL	0.4		5.0	9	1.0		10.0	Depression. Peat layers at 9 ft (native?)
50	70+25	25 ft N. of lights on paved shoulder	0.2		5.0			Rock	9.0	Drilled due to ACFEL report
51	62+70	25 ft N. of lights on paved shoulder	0.2		5.0	6.5	1.0	Clay/Rock	11.0	
52	62+70	5 ft N. of #51	0.2		5.0	7.5	2.0	Clay/Rock	9.5	
53	62+85	15 ft east of #51 and #52	0.2		5.0	5	5.0	Clay/Rock	12.5	
54	69+40	8 ft S. of runway CL	0.5		5.0			Rock	6.0	
55	77+75	Runway CL	0.5		5.0	5.5	0.5	Rock	7.5	Slight depression, very thick fill section
56	84+50	12 ft south of runway CL	0.5		5.0			Rock	7.0	Slight depression
57	94+80	18 ft south of runway CL	0.5		6.0			Fill	11.0	
58	96+55	33 ft N. of lights in paved shoulder	0.2		5.0			Fill	6.0	
59	95+80	21 ft S. of lights in paved shoulder	0.2		5.0			Fill	7.0	
60	93+00	36 ft N. of lights in paved shoulder	0.2	2.0	5.0			Fill	9.0	
61	89+75	24 ft S. of lights in paved shoulder	0.2		5.0			Rock?	7.0	
62	88+00	15 ft N. of lights in paved shoulder	0.2		5.0			Rock	7.0	
63	86+00	20 ft N. of lights in paved shoulder	0.2	0.2	4.5			Rock	6.0	
64	80+00	47 ft S. of lights in paved shoulder	0.2		5.0			Fill	7.0	Pore ice
65	73+00	48 N. of lights in paved shoulder	0.2		5.0			Fill	6.5	Excess pore ice
66	71+50	52 ft N. of lights in paved shoulder	0.2		5.0			Rock	9.0	
72	-	Inter. South Lp Twy and SE Lp	1.0		5.0	5.5	1.0	Clay/Rock	11.0	Excess pore ice

BH #	Distance	Description	AC thickness (ft.)	Thickness of Saturation Zone (ft.)	Frozen depth (ft.)	Ice depth (ft.)	Ice thick (ft..)	Refusal material	Bottom of Hole (ft.)	Remarks
		Twy								
73	-	Twy A 26 end 165 ft west of Vortac	0.3		5.0				7.5	Excess pore ice
74	-	Twy A West entrance to Cluster pit	0.2		5.0				6.5	
75	-	Twy A 48 ft east of culvert at low point	0.2		5.0				6.5	
76	-	Twy A 100 ft east of culvert at low point	0.5		5.0	6.0	1.0		6.0	
77	-	Twy A east entrance to CP 2&3	0.2		5.0	6.0	1.0	Rock	8.0	Big Depression
78	-	Twy A west entrance to CP 2&3	0.2		5.0	5.5	1.0	Rock?	6.5	Big Depression
79	-	Twy A btwn entrances to CP 2&3	0.2		5.0	7.0	0.5		9.0	Slight depression
80	-	Twy C east shoulder 150 N. of runway signage	0.2	0.3	5.0			Rock	6.5	
82	-	Twy A ax from Hangar 7 in shoulder	0.2		5.5			Rock	9.0	
83	-	Twy A and Twy C in shoulder	0.2		5.0			Rock?	7.0	
84	-	Twy A shoulder across from Hangar 7 & 8	0.2		5.5			Rock	8.0	

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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June 2013	Final	

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Kevin Bjella

5d. PROJECT NUMBER

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

In the late 1950s, white painting of the airfield at Thule Air Base, Greenland, was started to prevent thawing of ice-rich native permafrost soils that had caused localized depressions in the runway and taxiways. Unfortunately, the painting reduces the braking ability of the aircraft, and increases the costs of operation. Cost-effective alternatives to white painting do exist, such as insulating the subgrade, which was tested at Thule in this study, or over-excavating the ice-rich soils. These solutions can be implemented during the next repaving cycle, eliminating the white painting entirely, and saving future costs. Additionally, the white painting over the entire airfield should be halted. This will allow monitoring of thaw stability, better determining the ultimate extent of the few critical locations requiring thaw mitigation, and providing valuable information to efficiently design the thaw prevention techniques in the upcoming repaving. There will be some minor thaw settlement at a few areas during the time between halting painting and repaving. However, the settlement will not be catastrophic and will not decrease the reliability and operation of the airfield, and can be repaired with knowledge and equipment currently available. Diligent monitoring for any settlement will ensure that this procedure creates no adverse impact.

15. SUBJECT TERMS

Greenland	Permafrost	Thaw stability
Ice-rich soils	Runway maintenance	Thule Air Base
	Runway subsidence	White painting of runway

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
U	U	U	None	89	

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